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IMPLEMENTING SET BASED DESIGN INTO DEPARTMENT OF DEFENSE ACQUISITION

by

Team SBD
Cohort 311-152P

December 2016

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requirements for the degrees of

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ABSTRACT

This report provides guidance to implement the Set Based Design (SBD) methodology into the Department of Defense (DOD) acquisition framework. Deferring requirements and design decisions is the essence of SBD, which in turn defers cost commitments, allowing more flexibility to management than traditional design methodologies. This reduces the risk for cost and schedule overruns, both of which are perennial challenges for the DOD. This report identifies the original SBD principles and characteristics based on Toyota Motor Corporation's Set Based Concurrent Engineering Model. Additionally, the team reviewed DOD case studies that implemented SBD. The SBD principles, along with the common themes from the case studies, are then analyzed, and guidance is presented for implementing SBD into the Navy's 2-pass/6-gate acquisition governance process as dictated by the Secretary of the Navy acquisition instructions. Recommendations are provided on the system factors, such as program type and tool infrastructure, that provide a good fit for utilizing SBD. The cost and schedule differences between SBD and a typical point-based design approach are discussed. Finally, this report summarizes the findings and provides program managers and systems engineers an implementation method for SBD in DOD acquisition.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	amphibious assault vehicle
ABL	allocated baseline
ACAT	acquisition category
ACV	amphibious combat vehicle
AF	assessment framework
AoA	analysis of alternatives
ASN(RD&A)	Assistant Secretary of the Navy for Research, Development, and Acquisition
ASR	alternative system review
ASSET	Advanced Surface Ship and Submarine Evaluation Tool
ASW	anti-submarine warfare
AW	air warfare
C2	command and control
CAD	computer aided design
CAE	component acquisition executive
CBA	capability based assessment
CCW	capability concept wheel
CD	contract design
CDD	capabilities development document
CDR	critical design review
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations

DIT	design integration team
DOD	Department of Defense
DODD	Department of Defense Directive
DODI	Department of Defense Instruction
DON	Department of the Navy
DOORS	Dynamic Object Oriented Requirements System
EC	enabling capability
EFV	expeditionary fighting vehicle
EMD	Engineering and manufacturing development
ERS	engineering resilient systems
FACT	Framework for Assessing Cost and Technology
FDD	functional design document
FFRDC	Federally Funded Research and Development Center
FRD	functional requirements document
FV	fleet valuations
GAO	Government Accountability Office
HITR	high impact tradable requirements
HWS	high water speed
ICD	initial capabilities document
LCAC	landing craft, air cushion
LCS	littoral combat ship
LD	logical decision
LDUUV	large displacement unmanned undersea vehicle
LEAPS	Leading Edge Architecture for Prototyping Systems

LITR	low impact tradable requirements
LRIP	low rate initial production
LWS	low water speed
MBSE	model based systems engineering
MDA	milestone decision authority
MDAP	major defense acquisition program
MDD	materiel development decision
MITR	medium impact tradable requirements
MIW	mine warfare
NAVSEA	Naval Sea Systems Command
NRDE	Naval Research and Development Establishment
NUWC	Naval Undersea Warfare Center
ONR	Office of Naval Research
PBD	point based design
PBL	product baseline
PD	preliminary design
PEO	program executive office
PM	program manager
PMA	primary mission area
ROI	return on investment
POR	program of record
R3D	resources, requirements review board
RD	requirements database
PDR	preliminary design review

RFP	request for proposal
RSDE	rapid ship design environment
SBCE	set based concurrent engineering
SBD	set based design
SDS	systems design specification
SE	systems engineering
SECNAV	Secretary of the Navy
SEP	systems engineering plan
SOW	statement of work
SRR	systems requirements review
SSC	ship to shore connector
SUW	surface warfare
SWAP-C	space, weight, power, and cooling
SWBS	ship work breakdown structure
SYSCOM	Systems Command
TD	technology development
TDP	technical data package
TRL	technology readiness level
TSS	trade space summary
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology and Logistics
USMC	United States Marine Corps
UUV	unmanned underwater vehicle

EXECUTIVE SUMMARY

Set Based Design (SBD) is a systems engineering methodology that explores design combinations via a systematic elimination of infeasible sets until reaching a solution. By utilizing concurrent design efforts while deferring detailed requirements until they are fully understood, this methodology has the potential to replace the current point-based design structure in DOD acquisition, which have been plagued by cost and schedule overruns. Scope creep and requirements volatility in point-based design implementations often result in major rework, a major contributor to the cost overruns and delays in fielding systems to the warfighter. Deferring requirements and design decisions is the essence of SBD, which in turn defers cost commitments allowing more flexibility to management, reducing the risks for cost and schedule overruns. Although there have been efforts to use certain aspects of SBD in acquisition, it has not been leveraged to the maximum extent, nor are there any official guidelines or instructions for implementing SBD. The objective of this report is to take the major principles and characteristics of SBD and provide guidance on integrating these factors into DOD acquisitions. Through examination of industry studies and DOD instances of SBD, this report presents recommendations for tailoring the acquisition process within governing literature.

Toyota Motor Corporation employs a unique design approach that has been dubbed "Set Based Concurrent Engineering," or SBD. Sobek and his team identified three major principles of SBD: mapping the design space, integrating by intersection, and establishing feasibility before commitment (Sobek et al. 1999). Within these principles, SBD is further broken down into supporting principles to provide a guide for the implementation of SBD. Ghosh and Seering also examined Toyota, along with other instances of SBD, and published a list of the seven characteristics of set based thinking. The characteristics serve as a "how to" guide as well as emphasizing a particular organizational structure that enables SBD (Ghosh and Seering 2014).

The characteristics are:

1. Emphasis on Frequent Low-Fidelity Prototyping
2. Tolerance for Under-Defined System Specifications
3. More Efficient Communications among Subsystems
4. Emphasis on Documenting Lessons Learned
5. Support for Decentralized Leadership Structure and Distributed, Non-Collocated Teams
6. Supplier/Subsystem Exploration of Optimality
7. Support for Flow-up Knowledge Creation

This report considers the seven characteristics along with the three principles identified above which form the foundation of SBD for the implementation guidance being recommended.

Keeping these principles and characteristics in mind, examples of the use of SBD in DOD system acquisition are examined to determine if SBD was beneficial and if SBD could be applied to government acquisitions successfully. Each of these systems utilized Set Based Design in the design process. Four case studies are reviewed for the SBD impacts: the Ship to Shore Connector, the Amphibious Combat Vehicle, the Small Surface Combatant, and the Large Displacement Unmanned Underwater Vehicle. An additional section in this chapter covers a study conducted by Naval Surface Warfare Center Carderock Division, in which the Carderock employees examined the differences between point-based design and SBD and their impacts on a ship design, resulting in several takeaways. In all cases, design development was not limited to a single solution, and by delaying design decisions until realizing and understanding trade-offs, a longer period for stakeholder influence and feedback resulted. However, there were some drawbacks. In some cases, there were higher initial costs and commitment of resources upfront to conduct the SBD analysis than in a point-based design implementation. There was also a lack of education and experience in the execution and implementation of SBD. Overall, the use of SBD in the case studies has proven beneficial, to include the case study takeaways and their use of the three principles and seven characteristics of SBD.

The high-level governing document for DOD acquisition is the *Operation of the Defense Acquisition System* or DODI 5000.02. This instruction provides guidance to the services for interpretation and implementation of acquisition processes. For the Navy, the Secretary of the Navy has signed his own instruction, Department of the Navy *Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System* or the SECNAVINST 5000.02E. This lays out a system for acquisition within the Navy and Marine Corps, which has a 2-Pass/ 6-Gate process for meeting the required goals per Milestones A, B, and C within the DODI 5000.02. After analyzing the Navy's acquisition process, two guiding strategies for employing SBD within the current framework emerge. The first scenario is to incorporate the use of SBD from pre-Milestone A, or the Material Development Decision, until Milestone B. This strategy would result in a Request for Proposal (RFP) to the defense industry to complete the detailed design of the system. The second option would be to implement SBD from the same origin as the first scenario, but continue the SBD efforts until meeting the entrance criteria for Milestone C. This would result in a Technical Data Package to enable a production RFP to a defense industry vendor, or to produce Low Rate Initial Production items for testing and other Milestone C entrance activities. The focus of the implementation is to look for the system design attributes that have the largest impact on design instead of narrowing down to the requirements right away. Acquisition programs would then take the high-level capabilities and group them based on mission or concept of operations. From these groupings, the design further narrows as infeasible sets are no longer viable, leaving an initial product baseline at the Critical Design Review.

The report also presents program factors for examination prior to adopting the SBD methodology. The team recommends instances when to use SBD based on the acquisition model utilized and the capability of the tools in-house to analyze all the sets of data to narrow the design. Cost and schedule risk factors are big drivers for the use of SBD. The upfront analysis conducted increases cost and schedule requirements early in the program life cycle, therefore changes in program development cost and schedule are

necessary if one pursues SBD. Utilizing SBD should minimize rework and thus, lower the risk of both cost and schedule overruns.

This report concludes that the strict construct of DOD acquisition does indeed support the SBD principles. Utilizing the lessons learned from Toyota, the derived principles and characteristics, and past uses of SBD in the DOD, guidance has been provided for consideration when implementing SBD as a systems engineering methodology.

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I. INTRODUCTION

A. BACKGROUND

In the ever-changing fiscal and geopolitical environment, recent defense acquisition reform has been aimed to reduce system development time and cost. One methodology examined as part of reform efforts is Set Based Design (SBD). Set Based Design is a systems engineering methodology that explores design combinations via a systematic elimination of infeasible sets until a solution emerges. The purpose of this study is to examine SBD and analyze its potential application to defense acquisition to grow military technologies and apply them to systems at a rate greater than that of our potential adversaries. The practice of SBD has merit both in the civilian and military sectors, yet has not been formally incorporated into the Department of Defense (DOD) acquisition life cycle. The study establishes recommendations for applying SBD methodologies, considering the potential advantages and risks.

B. PROBLEM STATEMENT

The United States needs to maintain maritime superiority as near peer threats expand their maritime capability. However, according to a 2013 Government Accountability Office (GAO) study, "The cost growth of DOD's 2012 portfolio of weapon systems [was] about $411 billion and schedule delays average more than 2 years" (1). One of the GAO recommended areas of improvement is, "identifying significant risks up front and resourcing them" (2013, 12).

Many weapon system development efforts are experiencing cost growth and schedule delays due to requirements volatility. The traditional method of point-based design (PBD) selects one alternative for development at the onset of the program (Ghosh and Seering 2014). A problem with PBD is that engineers do not fully understand requirements at this point and changes to requirements yield rework: "The typical goal [of traditional systems engineering] is to get the requirements and specifications nailed down as early as possible" (Kennedy et al. 2013, 11). Kennedy continues by describing the risk of nailing down requirements too early: "However, tightly specifying

requirements early in the project means that some of the critical decisions are made very early. If they are made with too little knowledge of what customers really want or what is technically possible, then rework is inevitable" (2013, 11). Rework equates to cost growth and schedule overruns.

The SBD methodology is one potential solution to this problem, as it has been proven in the commercial market. SBD is a design methodology used to expand the design space, including ample design possibilities, while delaying critical design decisions until the right time, to narrow the set of designs systematically by identifying and eliminating infeasible solutions, while integrating the intersections of feasible designs (Sobek et al. 1999). Applying SBD effectively means delaying critical decisions until a better understanding of the problem arises, potentially resulting in a timely and cost-effective identification of the right solution.

At this time, no activity has fully incorporated SBD, and there exists no DOD-wide and no Navy-wide guidance on how program managers can apply it to leverage the potential cost savings and schedule benefits through the reduction of rework. The purpose of this report is to provide such guidance for the acquisition community.

C. PROJECT SCOPE

This report considers how the DOD acquisition process can leverage the SBD methodology to deliver more affordable systems to the fleet faster. The research focuses on defining SBD and its core principles, as well as the understanding previous applications of SBD in both industry and the DOD, to gain insight into appropriate uses and implementation processes. Primary source documentation from several DOD programs, including the Ship to Shore Connector (SSC), the Amphibious Combat Vehicle (ACV), the Small Surface Combatant, and the Large Displacement Unmanned Underwater Vehicle (LDUUV), was used to develop case studies to better understand how SBD has been used in the past and determine how best to use it in the future. The objective, therefore, is to determine how to tailor an acquisition strategy to incorporate elements of SBD to manage cost growth and scheduling delays due to changing

requirements and the resultant design volatility. Additionally, we will provide guidance on what aspects of the acquisition environment would allow for such an approach.

The project reports on the following:

1. A description of the evolution of SBD, and its major principles and characteristics

2. An exploration of various implementations of SBD in the civilian and military sectors alike

3. A brief description of the governing documents for DOD acquisition

4. Identification of system types that make good candidates for the application of SBD

5. Identification of system types for which SBD would not be recommended

6. Recommended implementation practices and processes, within the governing instructions, for the use of SBD into the DOD acquisition life cycle

This project sought to answer the following questions:

1. What is SBD and how can it benefit defense acquisition?

2. What factors make a program a good candidate for employing a SBD approach in defense acquisition?

3. What effect does SBD have on overall system costs and risks in support of defense acquisition? Are the potential benefits worth it?

4. What instructions and processes would have to be tailored or revised to facilitate Programs of Record (PORs) to use SBD in their development activities?

D. SYSTEMS ENGINEERING PROCESS

The team employed a tailored waterfall process model in order to explore SBD applications in the support of defense acquisition and PORs. Figure 1 shows the roadmap, from post problem definition to project report.

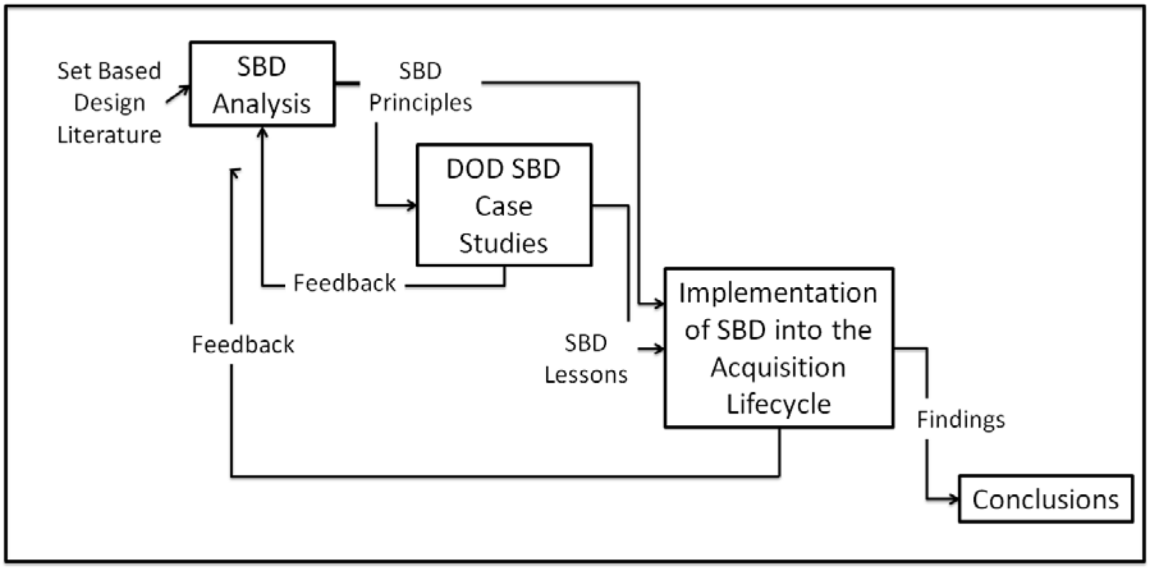

Figure 1. Capstone Engineering Process.

1. SBD Analysis

The team reviewed the SBD literature to define properly the SBD principles and characteristics utilized for the study. The history of SBD and the analyses of several case studies help determine the capabilities and limitations of SBD to better prepare for its introduction into the acquisition life cycle. This section was iterative in nature, based on lessons learned from the various case studies.

2. DOD SBD Case Studies

The team examined current applications of SBD in DOD acquisition. This process analyzed primary source SBD documentation in several defense programs, providing a history of the projects and programs, the issues and constraints, how SBD was utilized, and the successes or failures of utilizing SBD. By applying what we learned about SBD, we developed case studies to identify the potential benefits and programmatic risks of applying SBD to the acquisition life cycle.

3. Implementation of SBD into the Acquisition Life Cycle

The team studied the SBD principles and lessons learned defined from the previous phases and determined where the acquisition life cycle should adapt in order to

execute SBD. Feedback from the implementation changed the initial thoughts of the SBD Analysis and the principles originally defined. The focus centered on the major system engineering functions such as the analysis of alternatives (AoA), System Engineering Technical Reviews, and the prototyping test strategy, as found in the *Operation of the Defense Acquisition System* (DODI 5000.02) and Department of the Navy *Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System* (SECNAVINST 5000.2E). The team formulated a new Defense Acquisition Program model as well as requirements for the different technical reviews and decision points along the acquisition life cycle.

4. Conclusions

The team explored the findings and summarized the SBD implementation and lessons learned from the case studies reviewed. Based on feedback from each stage, the team was able to provide guidance for SBD implementation into the acquisition life cycle.

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II. REVIEW OF SET BASED DESIGN

This chapter explores SBD to set a solid foundation for our analysis. We present a brief history of SBD, starting with the origins from Toyota and its concurrent engineering concepts. Next, we present the high-level SBD principles and their supporting elements as determined by Ward and his coauthors in their 1995 work “The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster.” The decade following this work motivated additional research of the subject, one of which was “Set-Based Thinking in the Engineering Design Community and Beyond” by Ghosh and Seering in 2014. Ghosh and Seering reviewed Ward and other authors to provide their understanding of SBD methodology, consolidating the three principles presented by Ward et al. to two and naming seven characteristics of set-based product development. Finally, a look into the Wright brother’s development of the first manned, machine powered flight provides a concrete example of the potential cost savings and schedule benefits. Based on these works, and others, SBD was studied to provide a better understanding of its uses and potential implementation into the DOD acquisition life cycle.

A. HISTORY

Traditionally, the design approach to naval systems employed the use of Point-Based Design (PBD) to develop products. The execution of PBD is either employed in series or concurrently (Sobek et al. 1999). In serial PBD, a finalized component of the design passes to the designers of the next component. In concurrent PBD, designers choose an initial best solution approach, then iterate with increasing detail, incorporating feedback from other designers until the final design emerges. Figure 2 shows these two PBD approaches as practiced in an automobile design domain. The PBD serial engineering approach conducts engineering as a series of functions with minimal feedback loops. Before moving on to the next step, each previous function must be complete. The PBD concurrent engineering approach tries to conduct parallel processing

of the functions to obtain feedback earlier. However, both PBD approaches still require early design decisions with several stages of iteration on one solution.

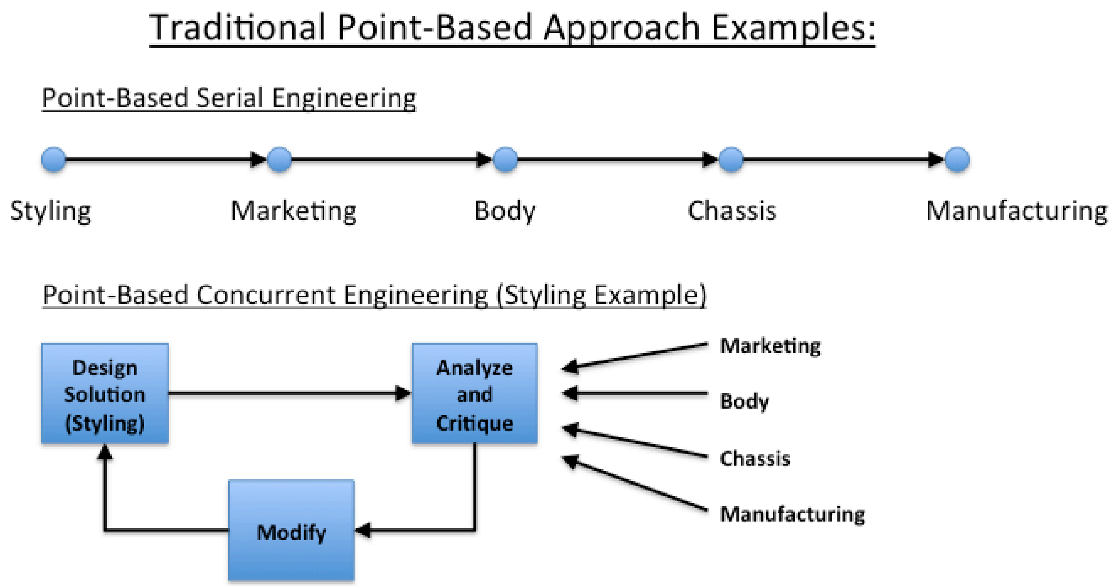

Figure 2. Point-Based Design Approaches. Adapted from Sobek et al. (1998, 69).

In naval systems, this iterative cycle generally initiates after one alternative from the AoA phase is chosen and pursued through preliminary design, critical design, developmental and operational test, full rate production, sustainment, and disposal, depicted as the design spiral shown in Figure 3. The classical design spiral follows the PBD serial approach where the satisfied constraints emerge from the consideration of each design requirement in sequence (Singer et al. 2009).

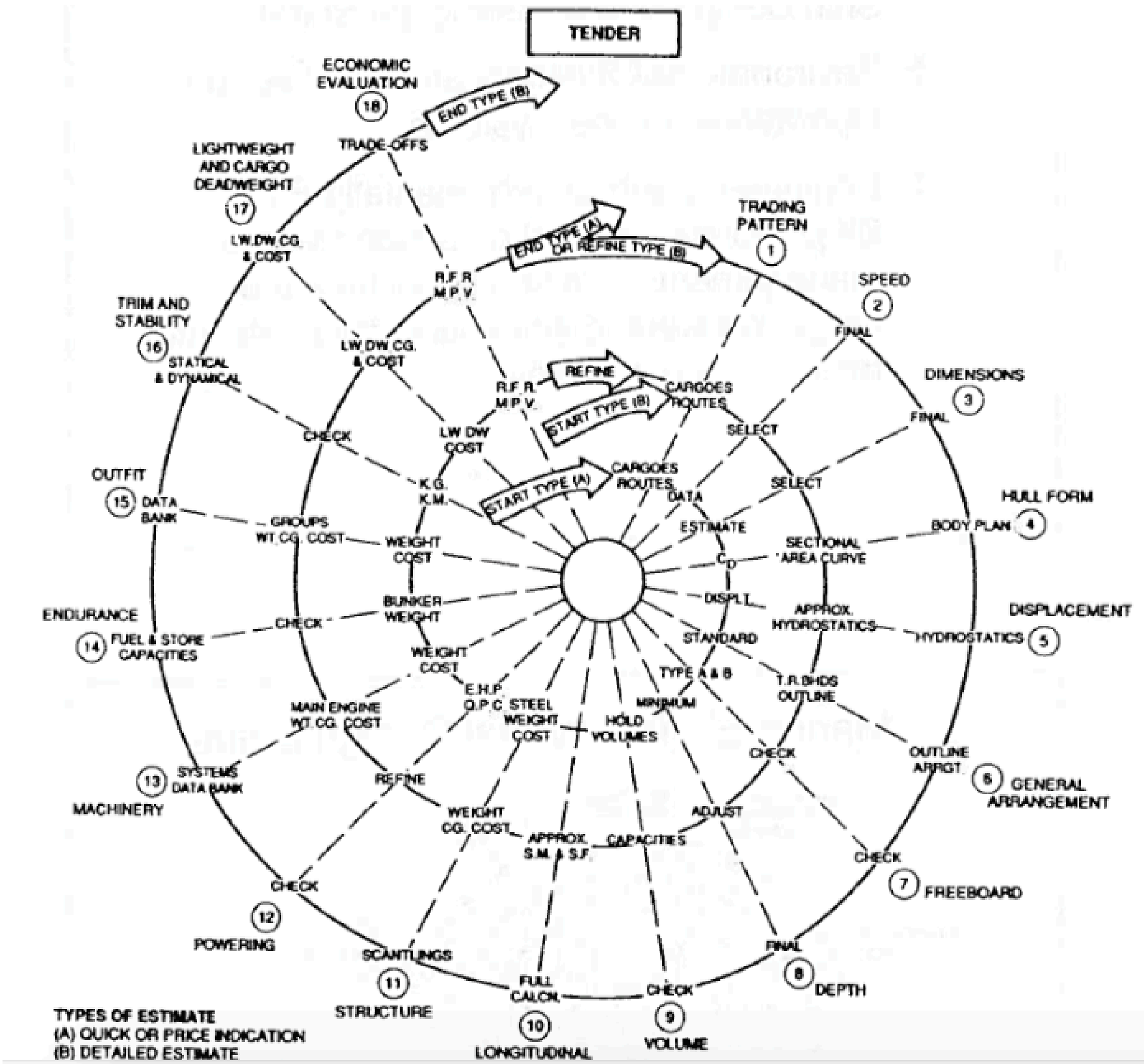

Figure 3. Classical Design Spiral. Source: Evans (1959, 692).

Efforts to speed up this iterative cycle to obtain the final design sooner at auto manufacturing companies in the United States have mostly focused on organizational changes, including the use of cross-functional, often collocated, teams to increase the speed and effectiveness of communications (Ward et al. 1995).

However, as systems have become more complex with an increasing need to produce effective designs more efficiently, the traditional approach to design, which narrows and fixes a design early, is being reconsidered (Kennedy et al. 2013). The old PBD approach leaves little ability to refine specifications later in the systems engineering process. Too often changes are being requested late in the design effort, when

requirements are better understood (Kennedy et al. 2013). The relative inflexibility of the PBD approach results in rework, as designers revert to the early design stages to select a new design, which fulfills the developing requirements (Kennedy et al. 2013). The alternative to staring over is to accept less effective designs, which is likely due to schedule and fiscal constraints; neither option is ideal.

SBD allows the design discovery for multiple efforts to take place, earlier in the design phase, before deciding upon detailed, finalized alternatives. More specifically, SBD allows multiple design options to remain viable and allows for feedback and influence from stakeholders throughout the design process. In doing so, requirements are understood better prior to making finalized decisions, and the final products better fulfill stakeholders' needs (Singer et al. 2009).

As early as 1995, Toyota Motor Corporation was one of the first to implement SBD successfully, resulting in the company becoming a leading competitor in the automotive industry (Ward et al. 1995). Toyota's implementation of SBD took the form of what they call Set Based Concurrent Engineering (SBCE). The "Toyota Model" is steeped in delayed decisions, ambiguous communication, and the pursuit of an "excessive number of prototypes," which helps Toyota to design better cars "faster and cheaper" (Ward et al. 1995, 44).

The main features of Toyota's design process, according to Singer et al. (2009) include:

1. Broad sets of design parameters [being] defined to allow concurrent design to begin

2. Sets [being] kept open longer than typical, to more fully define tradeoff information

3. The sets [being] gradually narrowed until a more globally optimum solution is revealed and refined

4. As the sets narrow, the level of detail (or design fidelity) increases

As demonstrated in Figure 4, each of the design aspects, including the marketing concept, styling, product design, components, and manufacturing system design, are kept

in work until an option is no longer viable and is eliminated, reducing the number of design options (Ward et al. 1995).

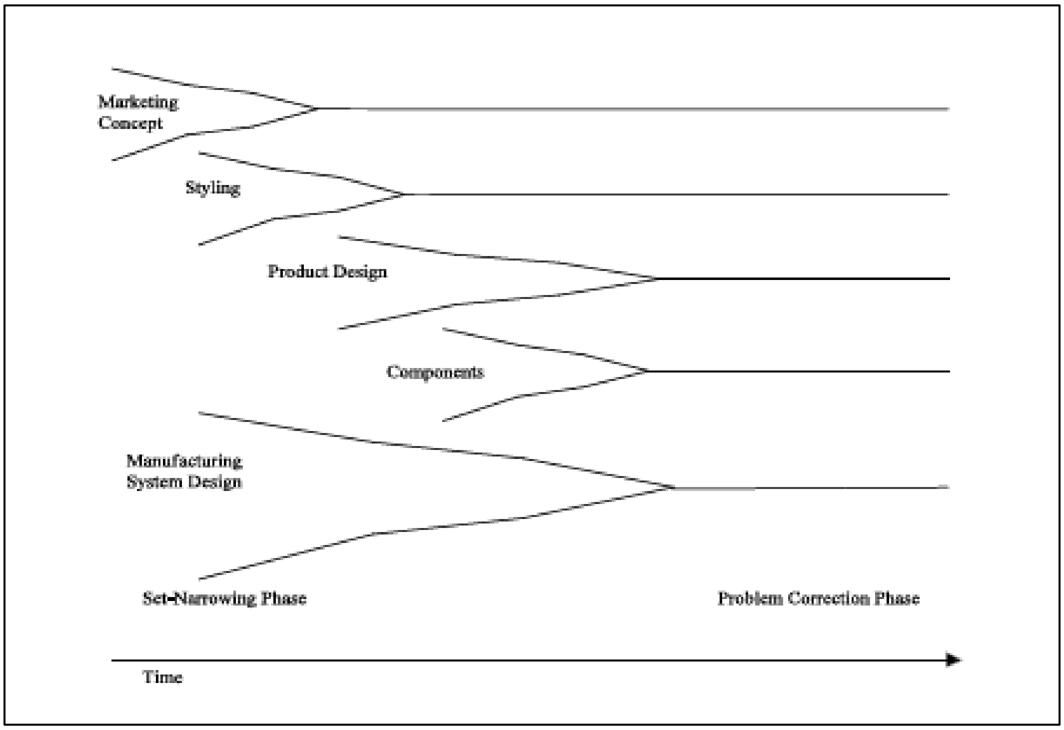

Figure 4. Parallel Set Narrowing Process Sketched by Toyota Manager. Source: Ward et al. (1995, 49).

This narrowing ultimately results in the optimum design solution, which most accurately reflects the requirements needs of the stakeholders. The chapter lays out Toyota's design process and principles later on.

By delaying decisions, SBD, in practice, also allows Toyota and other SBD users to delay the commitment of costs. In general terms, by locking in the design early on with little understanding of the system, difficulty arises in the ability to influence that design without negative impacts to cost and schedule. This results in significant schedule delays and cost overruns, should the desire or need to make design changes be present. A study conducted in 1989, by a U.S. DOD Technology Assessment Team, "show[s] that seventy to eighty percent or more of the projected life cycle costs are built in at the planning and design stages" (Neel 1991, 11). Figure 5 corroborates the team's findings by showing

how a disproportionate amount of life cycle costs are committed by the design activities early on in the development phase of PBD (Singer et al. 2009). What Toyota strives to do is make their committed costs more closely match the depicted incurred costs: “SBD strives to reduce the Committed Costs to more closely follow the Incurred Costs” (Singer et al. 2009, 11). This technique is a risk mitigation for the overall budget.

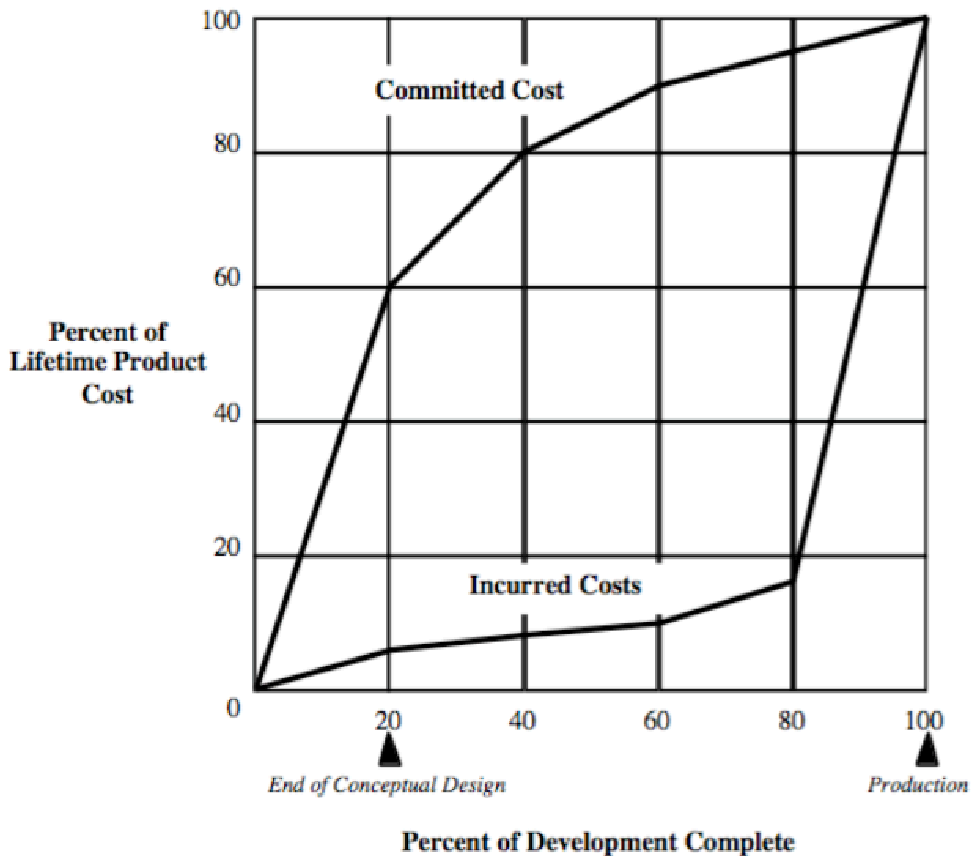

Figure 5. Depiction Rate of Life-Cycle Cost Commitment vs. Percent of Development Complete. Source: Singer et al. (2009, 11).

Due to the realities of PBD, much of these committed costs are the result of early design decisions, made with an insufficient level of understanding. Cost commitments and design decisions change, most often, only through the application of additional cost and time. It is for these reasons SBD practices and principles are superior to and revolutionize the traditional PBD method.

In order to more closely match committed costs to incurred costs, Toyota incurs additional development costs up front as a result of keeping alternative designs alive, to ensure they commit to the best overall design (Sobek et al. 1999). Compared to U.S. auto manufacturers, Toyota uses a significantly larger number of designs on the drawing board and at any given time they may have, “anywhere from five to twenty different styling alternatives” (Sobek et al. 1999, 25). This number of alternatives was excessive, and, until Toyota used its SBCE approach, was previously unheard of in the car industry. They have proven that the extra upfront engineering investment pays off, as they consistently occupy spots in the J.D. Power Top Ten for initial quality and time from program initiation to production. On average, Toyota was at the production phase in 27 months, versus 29 months at Nissan and 37 months at Chrysler (Ward et al. 1995). This is accomplished through the narrowing technique resulting in a robust design, requiring very little rework, more closely meeting stakeholders’ requirements. The final products proved to be industry successes.

Toyota’s success with SBD caught the interest of industry and government acquisition professionals, so much so that it inspired the Navy to begin considering alternatives to the traditional PBD acquisition process. The first use of SBD in Navy acquisitions took place in 2007 when Vice Admiral Paul Sullivan, Commander of Naval Sea Systems Command (NAVSEA), “agreed to allow the Ship to Shore Connector (SSC) Program to begin a government-led preliminary design (PD) and contract design (CD)” utilizing SBD (Buckley 2011, 79). In doing so, the SSC Design Team contracted Dr. David Singer, University of Michigan, to assist in the implementation. “Dr. Singer had conducted extensive research on the use of SBD for ship design” (Buckley et al. 2011, 80).

On February 4, 2008, Admiral Paul Sullivan sent a memo to his workforce encouraging the application of SBD in the acquisition process of shipbuilding (Singer et al. 2009). Following the use of SBD for the SSC, SBD proves to be a feasible alternative to traditional PBD acquisition in more recent systems acquisition programs. In the same year, the Secretary of the Navy (SECNAV) implemented a “2-Pass/6-Gate” process ensuring stakeholders are involved in the acquisition decision process from development

of the Initial Capabilities Document (ICD) through design and construction, in other words, between AoA and Pre-Preliminary Design which follows Milestone A.

B. SET BASED DESIGN PRINCIPLES

According to Dr. Raudberget, of Jönköping University Sweden, SBD or SBCE, as he calls it, has a different decision methodology from the traditional PBD. Raudberget says, "the SBCE decision process is based on a rejection of the least suitable solutions…SBCE carries forward all implementations that cannot yet be eliminated" (Raudberget 2010, 687). Through the rejection of the less desirable solutions, the designers methodically narrow the remaining set of solutions. This narrowing of alternative solution sets results in the best and final solution becoming evident. To do this, Sobek, Ward, and Liker suggest three SBD principles based on their research of the Toyota Motor development process. These three principles are Map the Design Space, Integrate by Intersection, and Establish Feasibility before Commitment (Sobek et al. 1999). Based on Sobek and his colleagues' studies of Toyota, they decomposed each SBD principle into three supporting elements, resulting in the following list:

1. Map the Design Space
    a. Define Feasible Regions
    b. Explore Trade-Off by Designing Multiple Alternatives
    c. Communicate Sets of Possibilities
2. Integrate by Intersection
    a. Look for the Intersection of Feasible Sets
    b. Impose Minimum Constraint
    c. Seek Conceptual Robustness
3. Establish Feasibility before Commitment
    a. Narrow Sets Gradually while Increasing Detail
    b. Stay within Sets Once Committed
    c. Control by Managing Uncertainty at Process Gates

1. Map the Design Space

The first principle, Map the Design Space, has three elements: Define Feasible Regions, Explore Trade-Off by Designing Multiple Alternatives, and Communicate Sets of Possibilities (Sobek et al. 1999). Sobek et al. observed distinct differences at Toyota versus their U.S. automaker counterparts. Toyota engineers explore and communicate numerous alternatives between their engineering divisions to gain a "thorough understanding of a set of possibilities" (Sobek et al. 1999, 73). Raudberget describes a set as "a palette of different solutions to a specific function or problem and can be seen as a family of design proposals" (2010, 687). To determine these sets, the feasible region must be defined (Sobek et al. 1999).

According to Sobek et al. (1999), to Define the Feasible Region, each functional department at Toyota determines, in parallel, the design constraints or "what cannot be done or should not be done" (73). These constraints are documented in the "engineering checklists (or design standards)" maintained by every engineering functional team on the project (Sobek et al. 1999, 73). These are not requirements or specifications but guidelines based on knowledge and experience of the details of numerous constraints such as functionality, reliability, manufacturability, government regulation. The space within these constraints is therefore the feasible region.

Once the feasible region is defined, Sobek et al. (1999) describe how the functional teams Explore the Trade-Offs of multiple design alternatives. They state that to do this, Toyota and its suppliers simulate and/or prototype system and subsystem alternatives. Single data points are much less useful than curves, so as much as possible, establishing relationships between parameters, via trade-off curves, enables a successful analysis. At Toyota, they value the reassurance of the best-chosen solution more than the inefficiency or cost that may have resulted from finding that solution, according to Sobek et al. For example, one Toyota exhaust supplier develops approximately 10 to 20 exhaust prototypes for each new Toyota car program (in an extreme case the supplier made 50 prototypes for one new car program). Sobek et al. continue, explaining that the exhaust supplier uses an engine supplied by Toyota with the prototype exhaust systems to produce trade-off curves for several variables, such as backpressure versus noise

reduction. In contrast, at Chrysler, the design team iterates on only the best idea. For instance, the Chrysler body-engineering group only considers the most likely design and does not begin detailed design until the styling is set. Toyota's body-engineering team develops two, three, or more of some body subsystems to determine the impacts of body styling before the final styling is determined (Sobek et al. 1999).

Communicating Sets of Possibilities is the third element of mapping the design space (Sobek et al. 1999). Communicating all sets of possibilities is critical in order to determine the best solution for the overall system. The exchange of the sets enables discovery of the best global solution, not just the best solution from a single functional engineering group's point of view (Sobek et al. 1999).

Toyota engineers communicate a variety of different information types and data. These communications are explicit and not casual (Sobek et al. 1999). One of the standardized forms utilized by Toyota engineers is a design matrix that simply compares alternatives on one axis to design criteria on the other, the comparison can either be qualitative or quantitative (Sobek et al. 1999). Table 1 depicts a qualitative comparison showing the range of performance or value for a particular function or attribute across various alternatives. Other information exchanged beyond discrete alternatives, includes lists of ideas, drawings, models, subsystem constraints and interfaces, trade-off curves, performance charts, and estimates (Sobek et al. 1999).

Table 1. Example Alternative Matrix. Adapted from Sobek et al. (1999, 76).

Matrix of Communicating Alternatives					
Alternative	Function 1	Function 2	Cost	Space	Etc.
X	⊙	⊙	◆	□	
Y	◆	□	○	⊙	
Z	⊙	◆	◆	○	
○- Excellent	⊙ - Acceptable	◆ - Marginal	□- Unacceptable		

2. Integrate by Intersection

The second SBD principle is Integrate by Intersection, which contains three elements: Looking for Intersections of Feasible Sets, Imposing Minimum Constraint, and Seeking Conceptual Robustness (Sobek et al. 1999). An intersection, defined by Sobek et al., is a solution that is satisfactory to all (1999). The purpose of identifying intersections is to determine which alternatives are feasible, so they can eliminate the infeasible. To do this, Toyota engineers focus on a solution that is best for the whole system. That is, each set considers all subsystems in that set, while making trades based on the collection of the complete set, not the optimization of each individual subsystem. In other words, it is a more holistic approach, and one functional area may give way in the interest of the whole. Even if such trades result in degraded performance in a given functional area, it is important that the system is maximized overall (Sobek et al. 1999). To do this, Toyota developers invoke the principle of "Nemawashi," which translates into doing the "groundwork," to include meeting and communicating with all stakeholders (Sobek et al. 1999, 77). Through this stakeholder interaction, they ensure that the developing requirements and technology are in fact contributing to a better overall design. The engineering efforts for the various attributes are concurrent and the overall solution concept is not set in stone; identifying the solutions that occur at the intersections of feasible sets is a crucial filter and reaffirms that the best overall system solution emerges within the remaining sets under consideration.

The second element of Imposing Minimum Constraint, as described by Sobek and his colleagues (1999), maintains design flexibility to make advantageous adjustments during integration as design exploration continues. The balance is to pose "just enough constraint" that each of the subsystems operates correctly, but no more, thereby enabling final design optimization (78). The practice manifests advantages in multiple places; one example is the interaction between the final computer aided design (CAD) drawings and the manufacturing die determination. Toyota initially sends CAD data to the manufacturing engineering group with no tolerances. The manufacturing group designs the dies to the nominal dimensions, stamps out the parts, and rivets them together. They identify flaws and determine which dies to modify that will fix the issue, are the least

expensive to modify, and will yield the best fit. The final dies and parts are the masters and the new reference for the design. From these masters, they update the CAD specifications to match the final part dimensions, instead of iterating the dies to meet the CAD.

The third element is Seek Conceptual Robustness, as stated by Sobek et al. (1999). A conceptually robust design will perform as intended in the face of final design uncertainty; therefore, it has a level independence from the final selected solution by other subsystems or functions (Sobek et al. 1999). When achieved, design works regardless of what the rest of the team decides to do and can be a great enabler to concurrent engineering efforts (Sobek et al. 1999). It also includes seeking a design that is tolerant to variations in market conditions (Sobek et al. 1999). Other benefits of conceptual robustness, noted by Sobek et al., are that it can collapse development time, improves serviceability, and is more easily upgradeable (1999).

One example of Conceptual Robustness in design is the strategy undertaken by a Toyota radiator supplier (Sobek et al. 1999). The supplier started by optimizing the cooling core design, then separating the radiator into the cooling core, upper and lower tank sections, and ancillary hoses (Sobek et al. 1999). They then redesigned the entire production line, in order to produce and finish any size or customized combinations of these major subcomponents on the line (Sobek et al. 1999). The result was a production line that tolerated variations in market conditions (the needs of their clients) and performed well regardless of the final design chosen (Sobek et al. 1999).

3. Establish Feasibility before Commitment

The third principle is to Establish Feasibility before Commitment (Sobek et al. 1999). The first two principles, and according to Sobek et al., Toyota’s SBD approach, support the third principle of establishing feasibility before committing (Sobek et al. 1999). The three elements of this principle deal with Narrowing Sets Gradually while Increasing Detail, Staying within Sets Once Committed, and Controlling by Managing Uncertainty at Process Gates (Sobek et al. 1999).

Narrowing Sets Gradually while Increasing Detail, is fundamental to reducing the significant number of sets. Unlike PBD, which focuses on ranking alternatives and selecting one alternative for further development, SBD looks to reject the least desirable solutions over time, thereby reducing the risk of incorrectly eliminating potentially suitable solutions until obtaining greater confidence (Raudberget 2010). As the number of sets under consideration narrows, development teams progressively elaborate each remaining set to enable better understanding of the relevant differences before committing (Sobek et al. 1999). According to Raudberget (2010), scoring and screening are methods of narrowing the number of sets; also, adding more constraints to help eliminate sets when multiple solutions meet current requirements.

Staying within Sets Once Committed, bounds the development effort and is critical to SBD, according to Sobek et al. (1999). They continue, stating that since designers are working concurrently and not fixing specifications, except the upper and lower bounds, it is critical that design teams stay within established sets of alternatives. Further, one development effort must have confidence that another effort will not jump to a solution outside the communicated sets.

The third element, according to Sobek and his colleagues is Control Uncertainty by Managing at Process Gates, intends to reduce uncertainty as needed, when needed (1999). They point out that at Toyota, uncertainty includes the size and/or number of sets under consideration and the level of detail attained. They observed control for the number of sets and level of specificity at design process gates. Further, they described that the required knowledge obtained and the number of sets vary according to the nature of the subsystem or component being developed. For example, at Toyota, they observed that due to the complex nature and long lead of the transmission subassembly, the "transmission gate" is much earlier than other subassemblies. As a result, Sobek and his associates stated that Toyota selects the transmission design years in advance of the start of production (1999). In contrast, they indicated that the exhaust system remains largely undetermined when the transmission is fixed. They found that Toyota would allow the exhaust system design to slowly narrow, finalizing the design only months before beginning production (Sobek et al. 1999).

C. SEVEN CHARACTERISTICS OF SET-BASED THINKING

Using the principles learned from Toyota's product development and various other applications of SBD, Ghosh and Seering developed seven characteristics of set-based product development in their more contemporary exploration of SBD. They took the characteristics and further boiled them down to what they considered the two major principles of set-based thinking: considering sets of alternatives concurrently and delaying convergent decision making (2014). These principles are no surprise, based on previous studies of Toyota, but the characteristics of set-based thinking are helpful to understand the application of SBD better and for making recommendations for the implementation of SBD into the DOD acquisition life cycle.

1. Emphasis on Frequent Low-Fidelity Prototyping

Frequent, low-fidelity prototyping is the idea that producing several design prototypes, without much detail, as Toyota has done, significantly improves the overall system design. This sentiment is echoed by Ward et al.'s explanation of Toyota's excessive number of prototypes and their contribution to creating more robust designs "faster and cheaper" (1995, 44). Admiral Richardson's sentiment of failing early and failing often embodies this notion of frequent low-fidelity prototyping that Ghosh and Seering (2014) deem so important to set-based thinking. The number and variety of prototypes open the design space vice limiting it, allowing for the design discovery and intersections of solutions to come together, as Sobek et al. (1999) described as their second principle. They are supported by Ghosh and Seering when they stated, "Notably, the proliferation of prototyping throughout the design process is a clear manifestation of concurrent development, as multiple prototypes help designers explore multiple concepts – which Toyota clearly understood and practiced" (2014, 3). These concepts comprise the whole set of possibilities for consideration and grants the design team creative license.

Another significant aspect of prototyping, as described by Ghosh and Seering (2014), is the emphasis of a low-fidelity prototyping process, reducing the cost of each prototype, while still allowing progress to continue in the product development process. These rapid, low-fidelity prototypes also avoid design fixation. Design fixation is akin to

the phenomenon known as “tunnel vision.” When the designers fixate on a particular design, which may not be the best solution, they lose sight of other, better quality designs: “Furthermore, recent studies…demonstrate that design fixation can be mitigated by generating rapid prototypes. Thus, by mitigating design fixation, designers enable themselves to consider a wider range of available options” (Ghosh and Seering 2014, 3). The idea of including a “wider range” of options, while eliminating infeasible designs, is a major tenet of SBD, as also described by Sobek and his colleagues (1999).

Sets of designs, as represented through prototypes, help to ensure, not only an overall cost savings for the project, in part due to the low-fidelity, but a better solution and a more robust design because of the accelerated learning from rapid, early prototyping. Admiral Richardson clearly sees the value, hence the need to work these processes into DOD acquisition.

2. Tolerance for Under Defined System Specifications

Tolerance for Under Defined System Specifications is having comfort with the lack of detail communicated prior to design, similar to the ambiguous communications as mentioned by Ward et al. and their description of the “Toyota Model” (1995). Contrary to the more traditional method of PBD, Ghosh and Seering explain the value of Toyota delaying design decisions and “not lock[ing] down specifications as soon as possible,” as other Japanese and U.S. automakers have done (2014, 3). Under defined specifications allow for flexibility and overall cost savings, as the design can progress, rather than going back to the drawing board, a sentiment echoed by Singer et al. (2009). This approach also allows the project to stay on schedule because they can continue to make progress as there is no need to “start over” while they increase the level of detail for the system specification. Design flexibility was present in the development of an airport Ghosh and Seering studied. The major lesson learned from the airport case study was that the flexibility that was afforded, due to delaying decisions, fostered an environment for concurrent design sets, which ultimately “mitigate[d] their exposure to risk from events such as shifting requirements or availability of materials” (Ghosh and Seering 2014, 3).

By refusing to commit to design specifications early and delaying decision in the product development process, flexibility emerges, the design space broadens, and risk lowers.

3. More Efficient Communication among Subsystems

Both reduced time and cost are the advantages of more efficient communication among entities working various subsystems. The difference between point based communication and set based communication is the increased time it takes to interact with all stakeholders, as well as the number of required iterations to successfully communicate and settle on a solution. "Ward et al. found support for [these] arguments in Toyota's product development processes, where Toyota and its suppliers were found to establish communication with each other less frequently for a shorter total duration of time than their U.S. counterparts employing traditional design methods, constant communication among collocated engineering teams was a given" (Ghosh and Seering 2014, 4). Essentially, bi-product of effective SBD employment is more efficient communication between engineering teams working various subsystems. Furthermore, speaking of the construction field, they state "that the ruling paradigm in the construction industry is a traditional, PBD approach featuring long delays in passing designs to different agents in the design process" (2014, 4). More efficient communications pave the way for a more succinct, rapid development of a system.

4. Emphasis on Documenting Lessons Learned/Knowledge

Set based thinking depends heavily upon documenting lessons learned and building a vast knowledge base to apply to future design development. The accrued technical knowledge, as Ghosh and Seering (2014) call it, allows mapping of the design space, a principle formed by Sobek et al. (1999). Additionally, the "lessons learned books" from previous years of Toyota body designs, "which, developed over fifteen years at that point, provide detailed knowledge of what potential designs can (and cannot) be implemented" (Ghosh and Seering 2014, 5). Important emphasis is on the potential designs that "cannot be implemented." This sentiment shows how documenting lessons learned specifically relates to Ward's idea of narrowing sets (1995), as well as the previously quoted Sobek et al. study, which states that SBD is about "determining what

cannot be done or should not be done" (1999, 73). If lessons learned are not documented and not influencing designs, the lessons will have resurface, which will have a negative impact on cost and schedule. That said, documenting lessons learned should improve life cycle costs and timeline. Keeping lessons learned and conserving the corporate knowledge allows for a more successful implementation of SBD.

5. Support for Decentralized Leadership Structure and Distributed, Non-collocated Teams

The way Toyota does business with its suppliers is a perfect model of a decentralized leadership structure in that the suppliers are not provided with requirements or specifications, they are allowed to make decisions based on what they perceive the needs of Toyota to be (Ghosh and Seering 2014). Suppliers' autonomy to work independently, and in a non-collocated fashion, is one of the advantages of SBD. Ghosh and Seering's proof of the success of a decentralized leadership structure in the software development industry provides another example. The "Scrum" methodology requires the division of labor into "Scrum Teams." Though normally collocated, they describe a case study "tracking a distributed team of 56 developers across three countries and witness[ed] the most productive Java development project to have been documented [up to that point] – a testament to set-based product development practices supporting distributed, non-collocated teams" (Ghosh and Seering 2014, 6). Decentralized leadership and distributed, non-collocated teams goes hand in hand with set-based thinking, as it fosters the first principle of SBD: "mapping the design space." It provides autonomy, which in turn promotes creativity to define the feasible region, explore tradeoffs with multiple alternatives, and communicate the set of possibilities.

6. Supplier/Subsystem Exploration of Optimality

By partitioning teams and decentralizing the leadership structure, the activities developing various subsystems begin to take complete ownership of their piece of the system. When individuals take ownership of a subsystem, they are committed to making it the most optimal solution as they can. As Ghosh and Seering explain, "[it] provides subsystems with greater autonomy in the design process, [encouraging] suppliers and

subsystems to take initiative in exploring optimality" (2014, 6). When teams have the opportunity to explore optimality, greater growth in technology and "breakthroughs" in product development occur (2014). When each team or subsystem works toward a more optimal solution, the overall design becomes more optimal.

7. Supports Flow-Up Knowledge Creation

Because of the decentralized leadership structure and distributed, non-collocated teams, communication flow reverses direction, from top-down to bottom-up, making the principles of SBD more applicable. As these teams are developing various sets of subsystems and making "breakthroughs" in technology, they communicate these advances to the "top," in this case, Toyota. The communication provided to Toyota allows them to "develop its specifications almost two years [later]" rather than providing the supplier with hard specifications (Ghosh and Seering 2014, 7). This broadens the design space for the suppliers, providing a larger set of possibilities. This style of organization, which allows for "flow-up knowledge creation," cultivates the principles of SBD and will most certainly aid in their implementation into the acquisition community.

D. POTENTIAL COST AND SCHEDULE BENEFITS OF SBD

Though it is difficult to distinctly state that the employment of SBD results in cheaper systems acquisitions for the DOD, there are several ways in which SBD has the potential to save money. One of the more significant ways SBD can prove to be more affordable is the reduction of rework. Kennedy et al. present the idea of reducing rework through the use of SBD (2013). They explain, "rework that occurs late in the product life cycle is dramatically more expensive than design work performed early in the cycle" (2013, 1). Utilizing SBD principles presented in this chapter will help to eliminate the drivers of rework. By studying dozens of companies, they learned that the primary causes of rework can be classified into three general categories:

> [1] The development team learns something critical late in the development process that invalidates prior assumptions or otherwise causes the team to revisit a prior decision [2]. The development team makes critical decisions too early in the project, before they have the knowledge needed to make a reliable decision [3]. Development team

members with one expertise inadvertently make decisions that overly constrain those of another expertise. (Kennedy et al. 2013, 4)

These three categories relate directly to the SBD principles and characteristics already covered. The first two categories go hand in hand with Toyota's practice of delaying critical decisions until more is learned, and therefore enabling a more robust decision. While more efficient, set based communications, described by Ghosh and Seering, would help alleviate the third of these categories. Going along with the three causes of rework, Kennedy et al. present three remedies for rework. They include accelerated learning, delaying critical decisions until sufficient knowledge is learned, and the application of set-based concurrent engineering (2013).

Kennedy and his coauthors herald the Wright brothers' development of the first airplane as one of the better-documented examples of using set-based practices to prevent rework. Their early work in the development of the airplane was more successful, quicker, and cost less than the work of other less successful developers like Otto Lilienthal, Clement Ader, Hiram Maxim and others (2013). Table 2, extracted from Kennedy et al., shows the contrast in timeline and cost between the early airplane development activities, for which none, other than the Wright brothers, successfully achieved powered manned flight.

Table 2. Powered Manned Flight Development Cost and Time Comparison. Adapted from Kennedy et al. (2013, 6–7).

	Timeline (years)	Cost ($)
Wright Brothers	4 (22 months of actual work)	<$1,000
Otto Lilienthal	11	No data
Clement Ader	25	$120,000
Hiram Maxim	~10	$200,000
Samuel Langley	16	$70,000

The Wright brothers achieved both the shortest timeline and cheapest overall cost. Kennedy et al. attributes this to their "accelerated learning" and set-based practices (2013). They changed the approach from a point-based method to a more set-based

method, which included more testing of ideas and prototypes up front. The point-based method described by Kennedy and coauthors was the "traditional design-build-test cycle" (2013, 6). Instead of taking this approach, the Wright brothers aimed to learn more about aerodynamics, so they designed and built the first wind tunnel to test various wing designs, so that they could learn critical information upfront before building full-scale airplanes. "Their focus was on learning first via careful testing of a variety of alternative wing designs" (Kennedy et al. 2013, 6). One of the seven characteristics of set-based thinking includes low fidelity prototypes, which is exactly what the Wright brothers did with their wind tunnel.

With these observations, Kennedy and his contemporaries describe practices to reduce the likelihood and amount of rework. They recommend three set-based practices to reduce rework:

> [1] Replace the design-test-build cycle with the test-before-design to accelerate learning in the early phases[2]. Specify customer and business interests as target ranges, giving the development teams room to explore, innovate, and find the most appealing tradeoffs[3]. Leverage set based knowledge to communicate the key issues from one area of expertise to another. (Kennedy et al. 2013, 16)

These recommendations have the potential to reduce rework and in turn reduce the overall cost and timeline, as seen with the Wright brothers' success.

E. REVIEW OF SET BASED DESIGN CONCLUSIONS

The SBD methodology has been juxtaposed to the traditional PBD strategy, analyzed for major principles, and broken down into characteristics. The principles Sobek et al. have provided are at the heart of SBD. They explain the importance of considering the set of all possible solutions, narrowing the possibilities by defining intersections of the feasible, and reducing the number of solutions only as they become infeasible, or not desired for some reason. Ghosh and Seering's characteristics serve as a "how to" guide for implementing SBD in any organization. The first four characteristics are helpful when defining processes for SBD's three major principles found in the Toyota studies. The last three characteristics focus on an organizational model to facilitate the various processes.

Ghosh and Seering provide a helpful, contemporary view of what SBD is and complements the principles of SBD that have been developed over the past couple decades by Ward, Liker, Sobek, Doerry, and many others. The foundation they have all set with respect to the understanding of what SBD is will be invaluable in showing how to implement SBD into DOD acquisitions. Ghosh and Seering leave the reader with several questions relating to the future works in SBD and determining when SBD is best suited. Through the examination of several DOD case studies in the next chapter, the goal is to try to answer some of their questions as it applies to DOD acquisitions and to provide some recommendations on how to change existing regulations to make it work. Kennedy et al. also provide a concrete example of how SBD has the potential to increase cost savings and decrease project timeline.

Figure 6 presents the three principles and seven characteristics visually, while showing how each of them either enables each other or depends on one another to work.

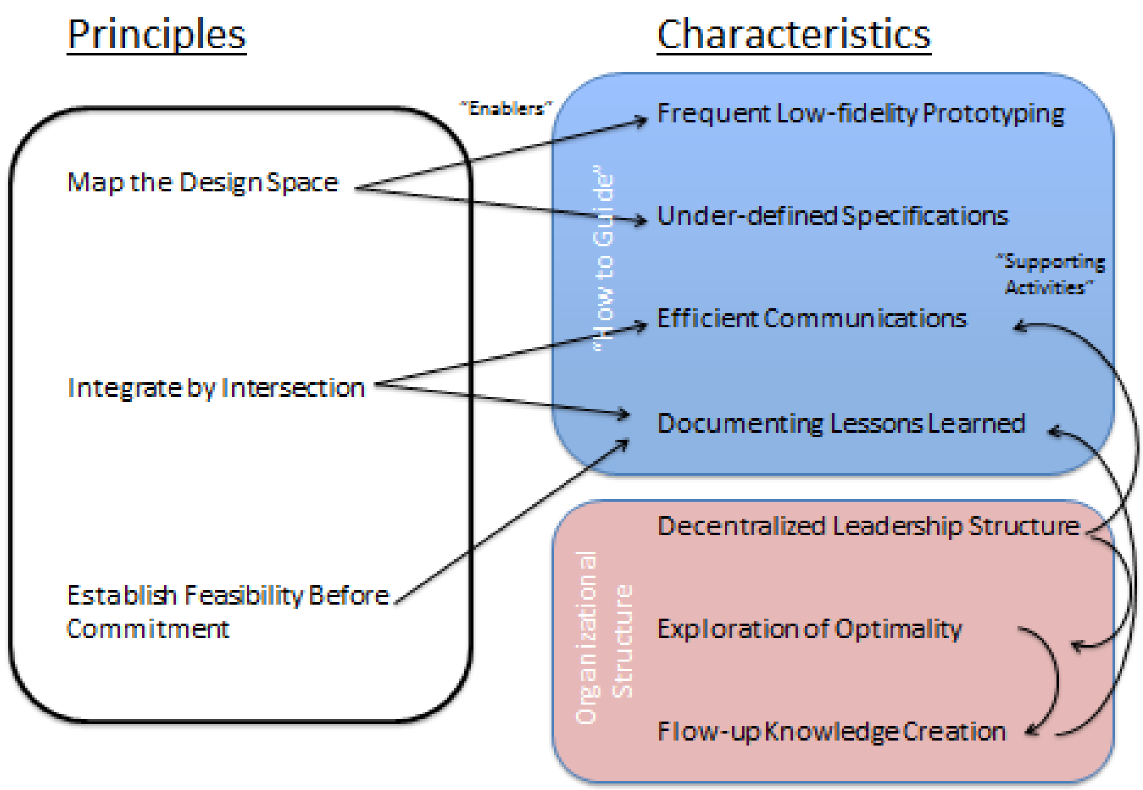

Figure 6. Principles and Characteristics of SBD.

The "enablers," as listed in the characteristics, are what allow the use of the principles of SBD, while the "supporting activities" show which of the characteristics support the others. These connections show the similarities and dependencies they share and to help visualize these during the case study exploration in the next chapter.

III. SET BASED DESIGN CASE STUDIES

In order to understand fully how SBD has fit into naval acquisitions in the past, it is useful to review case studies in which the Navy has made an effort to employ SBD principles and practices. From these case studies, one can glean lessons to determine which aspects or methods of SBD implementation have been successful and those that did not work so well. The following case studies include the Ship to Shore Connector (SSC), the Amphibious Combat Vehicle (ACV), the Small Surface Combatant, and the Large Displacement Unmanned Underwater Vehicle (LDUUV). With the knowledge of these projects, the goal is to take away lessons to better shape acquisitions, by determining how to implement SBD.

A. SHIP TO SHORE CONNECTOR

According to Buckley et al. (2011), the first application of SBD in the Navy was the SSC project. He explains that when Vice Admiral Paul Sullivan met with Deputy Assistant Secretary of the Navy for Ship Programs and Program Executive Officer for Ship Programs, they decided to begin government-led PD and CD. However, they desired to complete the schedule in under three years, therefore choosing to use SBD to "speed the process for analyzing craft and systems alternatives early in the design and also allow consideration of more of these alternatives" (Buckley et al. 2011, 79). They intended to speed up the process while maintaining design flexibility through understanding the design space, integrating by intersection, and establishing feasibility before commitment.

The SSC is the next generation Air Cushion Vehicle expected to replace the Landing Craft, Air Cushion (LCAC). They reported that at the completion of LCAC prototype, 91 craft were delivered to the Navy from 1984 through 2000, and they noted that the current LCACs began phasing out of service in 2015. SSC's requirements are similar to the LCAC to "transport equipment, personnel, and cargo from ships located over the horizon, through the surf zone, to landing points beyond the high water mark in a variety of environmental conditions" (Buckley et al. 2011, 80). They pointed out that if weight is overloaded, the craft sacrifices fuel and thus speed. Table 3 is a comparison of

specification requirements between the LCAC and SSC, showing service life, load capability, speed, sea state, and distance from shore.

Table 3. LCAC and SSC Capability Comparisons. Adapted from Buckley et al. (2011).

	LCAC	SSC
Service Life	20-year	30-year
Load Capability	60 tons	74 tons
Speed	35 knots	35 knots
Sea State	3	3
Distance from Shore	15 nautical miles	25 nautical miles

Buckley et al. (2011) explained that the government led team began PD in April 2008 in hopes of completing it in 12 months. They added that the short timeframe led the team to attempt the SBD process. They also indicated that the previous AoA completed in November of 2007 was a successful Gate-2 review of the 2-Pass/6-Gate process. (For readers unfamiliar with the Navy's Systems Engineering and Technical Review Process, a brief explanation is provided in Chapter IV.) The SSC Design Integration Team (DIT) consisted of the Ship Design Manager, the Deputy Ship Design Manager, and the Design Integration Manager. After DIT's approval of the internal requirements, they entered them into the Dynamic Object Oriented Requirements System (DOORS), a commercially available requirements traceability application. They noted that the design team used the ICD, the AoA Final Report, and the Resources, Requirements Review Board (R3B) to bind the requirements. They developed the Capabilities Development Document (CDD) at the same time.

After developing the CDD, Buckley et al. (2011) write that the team would use the ICD, AoA, R3B, LCAC specifications, and lessons learned to create the Functional Design Document (FDD). This FDD "was the set of operational requirements and derived parameters used to initiate the design effort" (Buckley et al. 2011, 83). They added the FDD is used to create the Functional Requirements Document (FRD), which captures evolving assumptions and requirements for an element in a trade space and contains the element-specific requirements. They indicated the FDD and FRD were used

to plan for PD as well as to create the draft SSC specification after being mapped to the Ship Work Breakdown Structure (SWBS). Once requirements were determined through the SWBS the SBD section took place. Figure 7 shows the preliminary design schedule with the SBD portion in the plans prior to PD (Buckley et al. 2011).

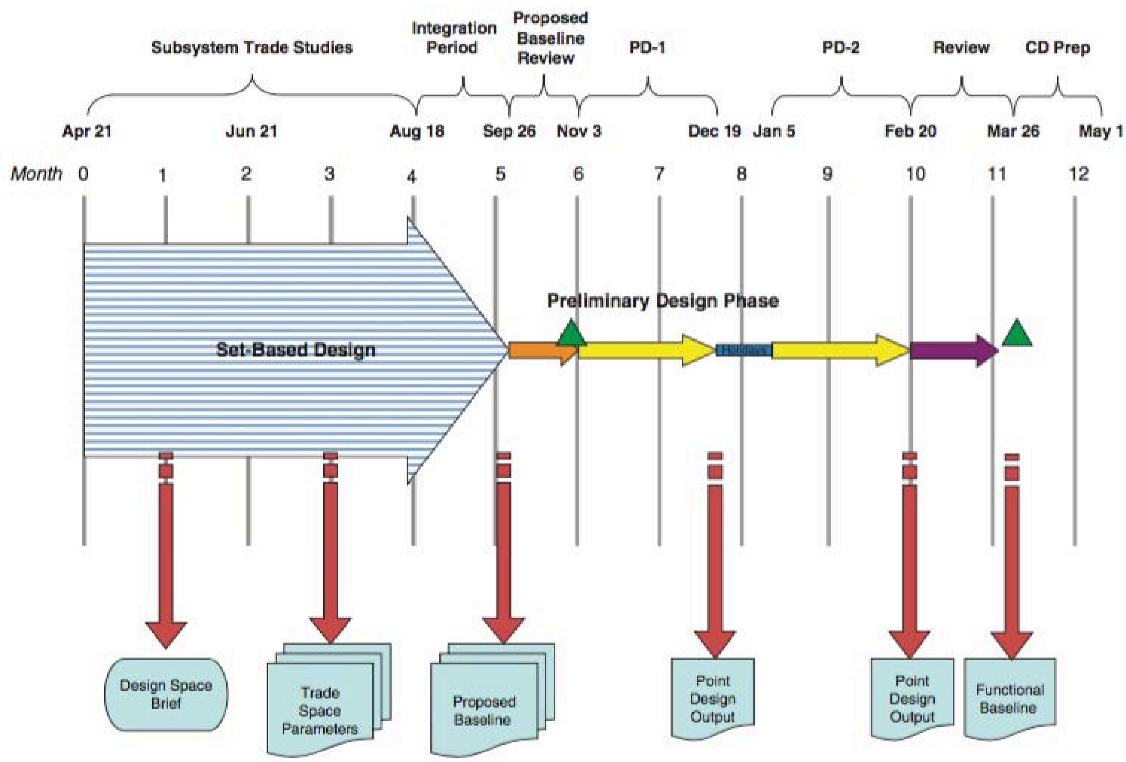

Figure 7. SSC Preliminary Design Schedule. Source: Buckley et al. (2011, 84).

During the SBD process, Buckley et al. (2011) reported that the designers conducted trade studies and spent the six weeks following integrating the systems into the baseline. The team briefed senior leadership the proposed baseline, which they concurred on and carried forward into PD. During the SBD process, the team communicated many variations of solutions consisting of different levels of performance and requirements for different regions of interest. Regions of interest included speed, length, beam of craft, load capacity.

Split teams covered different regions but continuously interfaced with each other on their findings and solutions, in order to eliminate infeasible options. Their design solutions would eventually converge, while conducting regression testing at the functional level (Buckley et al. 2011).

Furthermore, Buckley et al. (2011) write that the SBD phase was broken up into three steps including trade space setup and characterization, trade space reduction, and integration and scoring. They go on to explain that the trade space setup is similar to mapping the design space defined in Chapter II. They write that the trade space setup and characterization created Trade Space Summaries (TSS) that characterizes the element trade spaces, operational requirements, element specific attributes, and Technical Warrant Holders interaction results. They added the TSSs also track progress of trade space reduction, and improve and approve trade study plans. Buckley et al. explain the TSS for each element captured all design options with a thorough review. They added that the system engineer for that element A communicates with the system engineers from the other elements B, C, D, and all options from A are applied by the systems engineer from B, C, D, etc., and results of implementation are reported.

According to Buckley et al. (2011), Element Trade Space Analysis and Reduction is the next step in the SBD process to determine acceptable intersections of feasible sets. They relate this step to the Integrating by Intersection principle described in Chapter II. Furthermore, they show use for Designs of Experiments (DOEs) and other statistical tools in this process. Furthermore, Buckley et al. added Pugh matrixes to explore trade spaces and compare several designs. With these methods, the system engineers of the multiple elements could find the most feasible alternative. Then they used A Pareto analysis to find the best alternative with the lower cost and risk.

Finally, engineers completed integration and scoring for the SBD process. Buckley et al. (2011) equate this step to the SBD principle Establishing Feasibility before Commitment. They emphasize that at this phase the trade space still had 100 million potential designs. They explain the design team used brute force method to score and integrate the final options and that the team then screened the options for physical viability to reduce the alternatives further. After completion, they compared the

remaining alternatives for value with Logical Decision (LD) methodology. According to Buckley et al., the results of the LD, along with subject matter experts' judgment, led to two final designs: one, an aluminum alloy craft, and the second, a composite craft as SSC baselines.

For this case study, it is well documented that using SBD facilitated a wide variety of alternatives for review and that this thoroughly reviewed solution was chosen in a much shorter than expected time (Buckley et al. 2011).

B. AMPHIBIOUS COMBAT VEHICLE

Another example of SBD in the DOD is the U.S. Marine Corps (USMC) and the ACV program. The ACV is a system used to embark Marines from an amphibious ship and land them on the shore. Prior to the ACV, the USMC had been using the Amphibious Assault Vehicle (AAV) for over 40 years. However, as venerable as the AAV was, it was aging and the USMC was making way for the more contemporary Expeditionary Fighting Vehicle (EFV), the scheduled replacement for the AAV. Figure 8 is the legacy AAV in action.

Figure 8. Amphibious Assault Vehicle. Source: Burrow et al. (n.d., 2).

Burrow et al. (n.d.) explain the history of how the ACV came about. They claim that during the development of the EFV, the POR determined it to be too costly and have

excessive technical risk, so they cancelled the program. Concurrently, they noted that the USMC was studying the capability gaps of the AAV as compared to the current and future concept of operations (CONOPS). They were determined to pursue the new ACV. However, in the initial requirements identification stage, they eliminated the need for a high water speed (HWS) ACV. Furthermore, Burrow et al. state that the lack of a HWS capability was a concern and made senior USMC officials reconsider the program and embark on a feasibility study, based on capabilities trades, for a more affordable, HWS ACV. They wanted to determine if an acquisition program was beneficial for both cost and effectiveness (Burrow et al. n.d.). It is in this exploration of a new ACV that we see the use of SBD principles and techniques that the USMC deployed for the AoA.

An ACV Directorate was appointed to lead the study, which commenced in 2013 (Burrow et al. n.d.). They aimed to analyze four major areas: requirements, effectiveness, trade space, and affordability (Burrow et al. n.d.). The Directorate partitioned his workforce into teams to work in parallel using an SBD approach to explore their areas. This approach proved to be more effective and less time consuming than the point-based approach in which each design would be worked in a linear fashion, "tak[ing] over a year to complete, much longer than the [six to nine] months allocated" (Burrow et al. n.d., 3). According to Burrow et al. (n.d., 2), the teams set out to study the following:

1. Determine the feasibility and costs of producing a HWS ACV.
2. Identify and assess capability trades resulting in HWS ACV procurement costs.
3. Quantify, using modeling and simulation, and qualify, using active duty Marines, the operational benefits of a HWS ACV.
4. Determine the differences in development, procurement, and operations and support (O&S) costs between a low water speed (LWS) and a HWS ACV.
5. Identify the capability costs of a HWS ACV, i.e., the capabilities that can be provided on a LWS ACV that cannot be provided on a HWS ACV.
6. Evaluate the opportunity costs of a HWS ACV, i.e., impacts to other Marine Corps programs and accounts required to afford the HWS ACV.

Another SBD principle, reminiscent of Toyota's SBCE, is that "definite conclusions would not be made until very late in the study during the comparison of the alternatives" (Burrow et al. n.d., 3). By delaying decisions until the appropriate time, they analyzed the entire trade space, ensuring all possible designs are considered. To provide some insight into how many designs they studied, Burrow et al. (n.d.) stated that they ran 20 thousand different configurations for each of the four capability concepts, totaling 80 thousand different designs. Figure 9 shows a depiction of a traditional approach to the study as compared to the SBD approach.

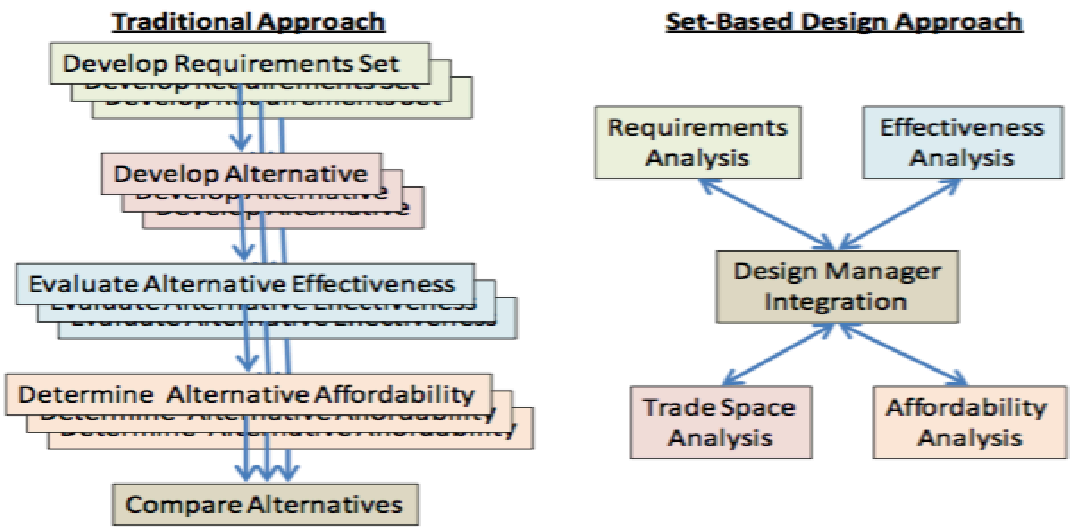

Figure 9. Traditional Approach vs. Set Based Design. Source: Burrow et al. (2014, 3).

The traditional method requires the study of a small number of chosen designs in which they employ the systems engineering process all the way to the AoA. This process is iterative and time consuming by nature but also restrictive in the design space. The SBD model for the study allowed the teams independently to study the entire scope of their domain, providing a wider set of solutions. By working independently to explore the various sets of designs, the team was able to save time and include a more comprehensive set of possibilities. The figure presents what Ghosh and Seering thought was so important to successful employment of SBD: "Support for Decentralized Leadership Structure and

Distributed, Non-collocated Teams" (n.d., 5). Employing this characteristic effectively by the ACV team, allowed them to finish the study in under a year.

Since this was a feasibility study, not all SBD principles or characteristics were completely exhausted, though they did indeed use all three major. The first principle, "Map the Design Space," or "what cannot be done…should not be done," eliminated the LWS region from the feasible design region, as they were specifically interested in an ACV with HWS capability (Burrow et al. n.d.). Another example of a Sobek et al. (1999) SBD principle is how the team was able to integrate at the intersection of these four areas (requirements analysis, effectiveness analysis, trade space analysis, and affordability analysis) to determine the final outcome of the study. "The final recommendation for the ACV would be based on an intersection of these four analyses" (Burrow et al. n.d., 3). By dividing and conquering, the study was able to accomplish the goals more efficiently and effectively.

One major assumption of the study was that the effectiveness analysis only depended upon five design components: water speed, personnel capacity, weapon system, under-blast protection, and direct fire protection (Burrow et al. n.d.). They categorized these design attributes as "big rocks" resulting from the fact they were the largest contributors to cost and weight. By doing this, the teams effectively mapped the design space, by defining the feasible region. For the trade space analysis, the assumed that only HWS alternatives were in consideration, and therefore, only varied the other four attributes to make thousands of different design combinations to study (Burrow et al. n.d.). Again, this is part of the mapping principle of SBD. On the other hand, the effectiveness analysis team studied the operational effectiveness of each individual attribute separately, regardless of the overall system configuration (Burrow et al. n.d.). This exploration of the effectiveness of each system is another example of dividing and conquering through distributed teams, but also invokes the characteristic of exploring the optimality. The requirements analysis team studied all additional requirements, while the affordability analysis team conducted their study as a separate activity.

The team integrated by intersection by looking for the intersection of feasible attributes, through modeling and simulation, as well as the principle of "Nemawashi."

Much like Toyota using communication with their suppliers and the “Flow-up Knowledge Creation” from Ghosh and Seering, the team utilized surveys of 250 Marines and held a workshop at Quantico for 24 Marines. They asked them to rank and rate the “big rocks” and other tradable capabilities in order of importance and level of criticality. The results allowed the team to narrow the feasible design space by applying a risk study based on user input.

The teams also invoked their own principle of “flexibility,” similar to Ghosh and Seering’s “Tolerance for Under Defined System Specifications,” to minimize the constraints and to control and manage the uncertainty at process gates. “Flexibility is defined for the ACV to mean that for a given requirement, the exact value for the requirement has not been established with certainty; the design must be able to affordably adapt to a specified range for the requirement’s value” (Burrow et al. n.d., 14).

Configuration modeling was the essential activity to this study. In order to compare different design attributes, they defined “capability concepts” as a complete vehicle that possessed varying levels of “big rocks,” along with a list of other requirements from the requirements study. “For example, a capability concept would refer to an ACV that carried 17 troops and weapon system ‘X’, and included under-blast protection level ‘C’ and direct fire protection level ‘B’” (Burrow et al. n.d., 5). As stated, all capability concepts were HWS capable. These “big rocks” included various combinations of troop capacity, weapon system, and under-blast and direct fire protection that were feasible, further narrowing of the design space. As previously stated, there were approximately 80 thousand possible combinations, which is contrary to the traditional approach in which they only analyze up to a few alternatives (Burrow et al. n.d.). They did not employ the traditional method in this study, “instead the “cloud” of all feasible configurations was used” (Burrow et al. n.d., 5). The trade study ultimately yielded 24 feasible capability concepts as a result of several simulations. These were established by exploring the “big rock” trade-space, while the requirements study identified approximately forty additional, tradable requirements, and were analyzed for cost and weight (Burrow et al. n.d.).

At the conclusion of the study, in January 2014, USMC officials were provided with the cost, feasibility, and risk analysis of an ACV acquisition program that provided them the ability to make a well-informed and confident decision to pursue the ACV. The underlying theme for the study was a set based approach which provided “the ability to develop in-depth knowledge of the technical problem and potential solution set, a risk-based understanding of what was feasible and infeasible, and high confidence cost estimates based on technical feasibility and diversity of solutions” (Burrow et al. n.d., 15). By employing SBD, the teams were able to design a large set of alternatives, expand the design space, and provide a solid analysis for the decision makers, resulting in the pursuit of the HWS ACV.

C. SMALL SURFACE COMBATANT

In 2014, the Navy created a Small Surface Combatant Task Force to assist the Secretary of Defense in budget deliberations. The Task Force for the Small Surface Combatant had several tasks. First, the team had to establish both the requirements and the trade space of the Small Surface Combatant. Then the team had to consider alternatives for the design concept: a modified Littoral Combat Ship (LCS) design, an existing ship design, and a new ship design. Each concept was to be explored for four major facets: top-level requirements, cost, Milestone schedule, and lethality to air, surface, and undersea threats (Garner et al. 2015, 1). Figure 10 displays the requirements analysis process that the task force utilized.

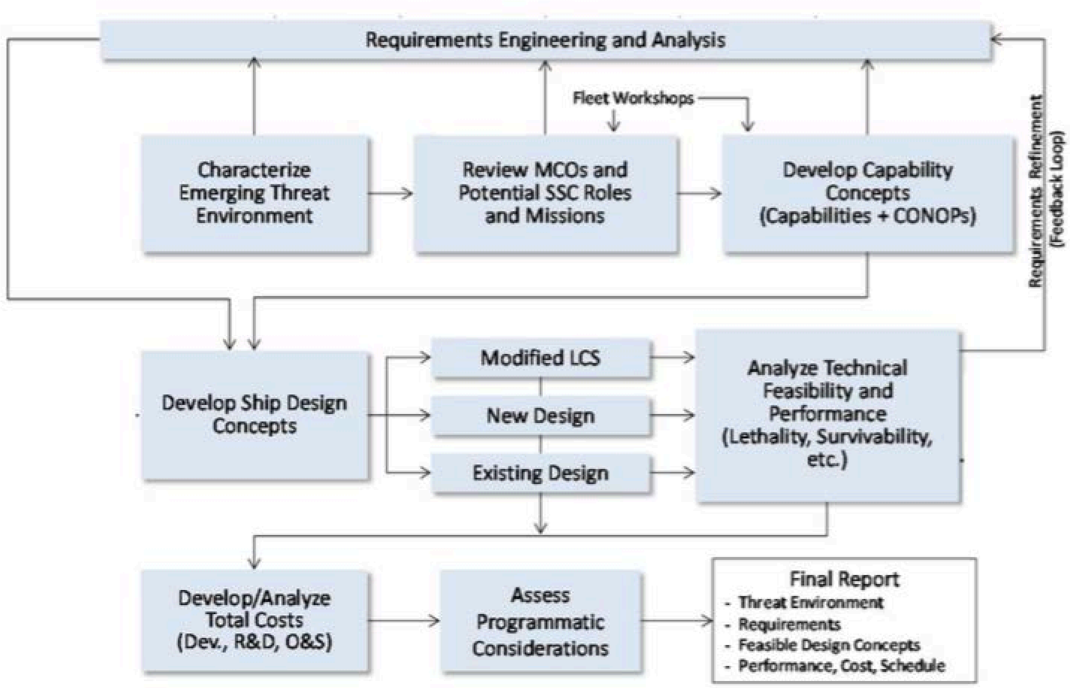

Figure 10. Small Ship Combatant Task Force Process. Source: Garner et al. (2015, 3).

The task force conducted multiple parallel efforts to define the mission areas and the capability concepts that defined the requirement trade space. Separate groups characterized the threat environment, reviewed the potential roles of the SSC, and developed the Capability Concept Wheel. All the groups provided continuous feedback in order to properly conduct the requirements analysis. Next, a parallel effort analyzed each of the three ship design efforts: a modified LCS, a new ship design, or an existing ship design. They then analyzed all of these alternatives for feasibility along with cost and programmatic concerns.

Set Based Design was utilized throughout this process taking points from the SBD principal concepts, as stated by Garner et al. (2015, 2):

1. Consider a large number of potential solutions.
2. Have specialists evaluate sets of solutions from their own perspective.
3. Intersect the sets to optimize a global solution and establish feasibility before commitment.

These three principles map closely to Toyota's original principles for concurrent engineering. The first two SBD principles relate directly to Toyota's "Map the Design Space." The task force looked to consider a large solution set while also designing multiple alternatives through specialists evaluating the solution set each with their own perspective. The last principle relates to Toyota's "Integrate by Intersection" and "Establish Feasibility before Commitment." The task force found intersections of feasible sets and stayed within the sets once committed.

The first step the team took was to create a Capability Concept Wheel as shown in Figure 11. Each wedge of the wheel has several configurations and opens up the trade-space. Each level in the wedge provided an increased capability. For example, one of the wedges on the bottom right is Underway Days. The level closest to the center is for 15 days, and it increases outwards to 30, 45, and 60 days. This allowed the team to evaluate the trade space for the different capabilities.

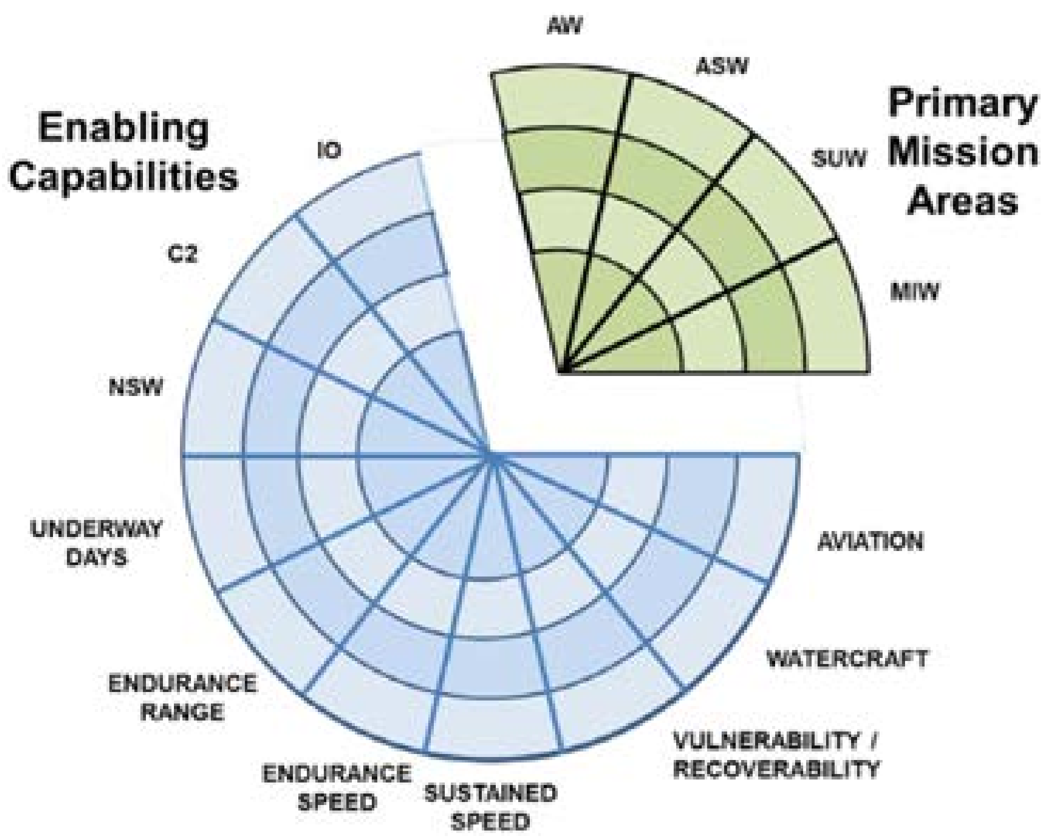

Figure 11. Capability Concept "Bullseye" Chart. Source: Garner et al. (2015, 2).

The task force focused on four mission areas: Air Warfare (AW), Anti-Submarine Warfare (ASW), Mine Warfare (MIW), and Surface Warfare (SUW). They considered the other elements enabling capabilities. The team utilized the different wedges and levels in the wheel to create 192 capability concepts. Each of the concepts provided different enabling capabilities for the Small Surface Combatant. Each were then examined and then narrowed down to 13. From there, they continued with eight because the ASW options were very similar. Table 4 displays the eight capabilities. Columns CC1 to CC8 list each capability concept. Each concept was mapped to the mission area capabilities, and the "X" was utilized to determine if the concept met the mission area capabilities.

Table 4. Capability Concept Mission Area Capabilities. Source: Garner et al. (2015, 4).

	Capability Concept							
Mission Area Capabilities	**CC 1**	**CC 2**	**CC 3**	**CC 4**	**CC 5**	**CC 6**	**CC 7**	**CC 8**
Self Defense against Air, Surface, Undersea Threats	X	X	X	X	X	X	X	X
Capability to detect and engage small craft within- the-horizon of own ship		X	X	X	X	X	X	X
Capability to achieve mission kill of over-the-horizon surface targets					X	X	X	X
Capability to detect and engage undersea threats in support of ASW operations	X		X	X			X	X
Limited capability to defend other ships against ASCMs	X	X		X		X		X

Combat system engineers then modeled all of the concepts, created alternatives for each of the capability concepts, and ran them through a detect-control-engage kill chain simulation analysis. They estimated Space, Weight, Power, and Cooling (SWAP-C), costs, and manpower to design three options: a modified LCS design, an existing ship

design, and a new ship design. Then they analyzed Feasibility, cost, and for each of the designs.

For the LCS modifications, several excursions were conducted which traded enabling capabilities (EC) to preserve primary mission area (PMA) capabilities, traded PMA performance to levels that would still provide operational utility, and implemented engineering tradeoffs among design features to address SWAP-C and center of gravity concerns. This excursion analysis was an important element in helping to explore fully the design trade space, as it explored means to increase space, weight, power, or cooling, or lower center of gravity to provide additional trade space for capability concept exploration (Garner et al. 2015).

The new ship design utilized Advanced Surface Ship and Submarine Evaluation Tool (ASSET) and Rapid Ship Design Environment (RSDE) to create the design space of over 15,000 different configurations. The designers placed these configurations into the Engineering Resilient Systems (ERS) Trade space Toolkit as shown in Figure 12. They implemented five models: Combat Systems calculator, regression models, cost models, feasibility element calculator, and a configuration feasibility calculator. Utilizing a Monte Carlo simulation, a subset of values emerged that mapped to the Capability Concept and the others randomly chosen. From those, the feasibility of each was determined based on the risk level for operational success.

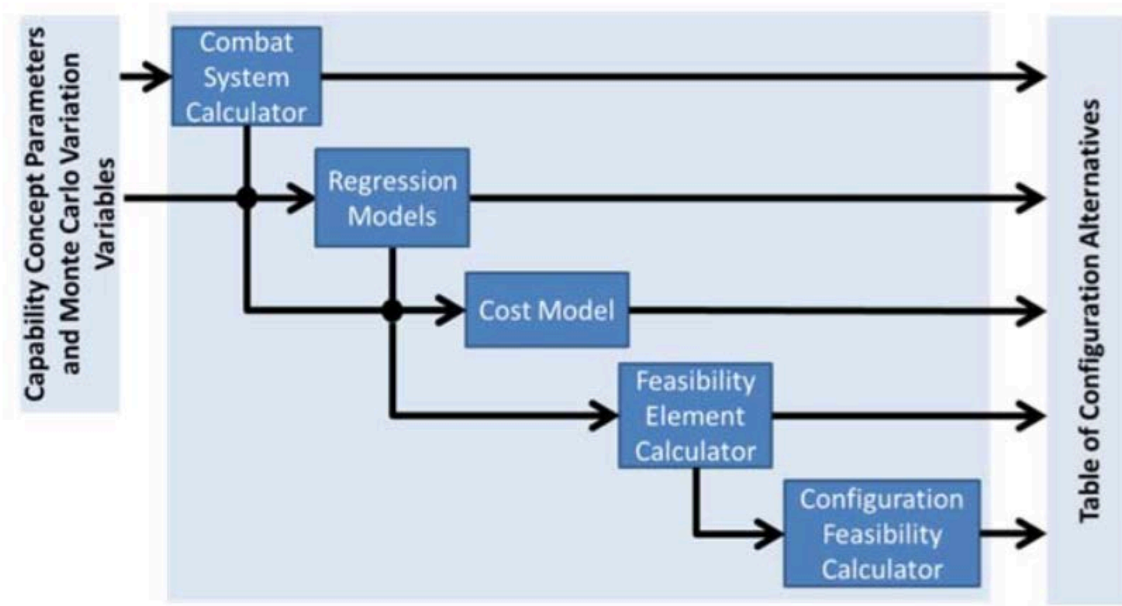

Figure 12. ERS Trade Space Toolkit Structure. Source: Garner et al. (2015, 7).

By employing SBD processes, the task force evaluated thousands of design alternatives and provided the leadership insight to make acquisition decisions within six months. Adhering to the three methods allowed the task force to analyze thousands of potential solutions, analyze all the design alternatives in parallel, and find intersections in the feasibility to establish the overall operational risk of those solution sets. Specialists, such as the combat systems engineers, evaluated from their perspective and the feasibility calculator enabled the team to establish feasibility of the solutions before commitment to the design. The Secretary of Defense accepted the task force recommendation to build a new Small Ship Combatant ship based on an upgrade to the LCS.

D. THE LARGE DISPLACEMENT UNMANNED UNDERWATER VEHICLE[1]

The final case study explores an SBD implementation process, which is currently in progress for a POR. This analysis will focus more on the steps of implementation and the types of tools needed to employ SBD to a developing system. The program of interest

[1] A significant portion of the information contained within this chapter is based on personal knowledge of one of the authors who has worked within the LDUUV program.

is the LDUUV and the programmatic details shared will be kept generic to avoid violating Defense distribution and dissemination regulations of technical documentation.

The LDUUV will provide the Fleet more undersea military capability in terms of endurance, operational range and modular payloads. The LDUUV will extend the footprint of the warfighter with launch and recovery integration for the Virginia-class and the Ohio-class guided missile submarines as well as littoral combat ships. The program, established by the Unmanned Maritime Systems Program Office, resides in the Program Executive Office (PEO) Littoral Combat Ships.

In early 2016, the PEO LCS (Milestone Decision Authority) ceased the release of the Request for Proposal (RFP) to industry and decided to have the design led by a government team at Naval Undersea Warfare Center (NUWC) Newport, in partnership with other Warfare Centers and industry as necessary to design and integrate the system. They also wanted to use the growing systems engineering methodology of SBD to field a more reliable system through highly controlled design techniques, reducing the probability of scope creep, rework, and cost and schedule overruns.

The program was near RFP release, which equates to being between Milestones A and B; more specifically, post Gate 4 of the Department of the Navy (DON) 2-Pass/6 Gate requirements/acquisition process. They sought to implement SBD at this point. The CDD was the main tool to map properly the design space, as discussed in detail as one of Toyota's three main principles. These capabilities form the initial LDUUV Capability Concept and facilitate further decomposition and mapping efforts for Measures of Effectiveness, Measures of Performance, and Key Performance Parameters. The CDD was essentially the driver for the LDUUV design space and furthermore the solution sets.

A "Capability Concept" as referenced above, combines a requirement set with a CONOPS. Changing the requirements and/or the CONOPS will produce a different capability concept that will lead to a different set of solutions.

The plan for how to use SBD is currently in flux; program schedule and funding limitations have created an increasingly dynamic environment. The high-level process remains stable but the inputs and outputs of the plan are not final. For example, they

originally planned SBD at different levels of system development. Level one focused on achieving a subset of the CDD based on technical and stakeholder prioritization, as well as “integrating by intersection” of four major high impact tradable requirements domains: Forward Looking Sonar, Synthetic Aperture Sonar, Energy, and Wet versus Dry Architecture. Ranges of solutions for the four domains would be paired down through more detailed analysis (such as Model Based Systems Engineering) to create a final design recommendation for prototyping. The results of the prototype testing influenced the future SBD analysis of level two, which included all the CDD requirements, therefore creating a larger trade space. Ultimately, in level two, the result of the SBD analysis produced a second prototype that finalized the technical data packages for low rate production turnover to industry.

As the scope of the SBD effort became more robust along with the pressures of the strict schedule and funding hardships, they realized that to ensure the first prototype is complete by the set milestone, SBD will be diverted from influencing the first prototype; the first prototype will be an accelerated learning input into the SBD process. This aligns with Ghosh and Seering’s Tolerance for Under Defined System Specifications (2014). This input informs the design team and decision makers of the refined requirements to pursue, but the trade space remains open until further input and analysis is complete.

As stated earlier, the process for implementing SBD into the LDUUV remains somewhat fixed and the execution of this process is still in its infancy, though the finer details for the execution of SBD are not determined. Figure 13 is the overall scope of steps for using SBD as well as showing the needed resources/ tools to guide the process from inception through realization.

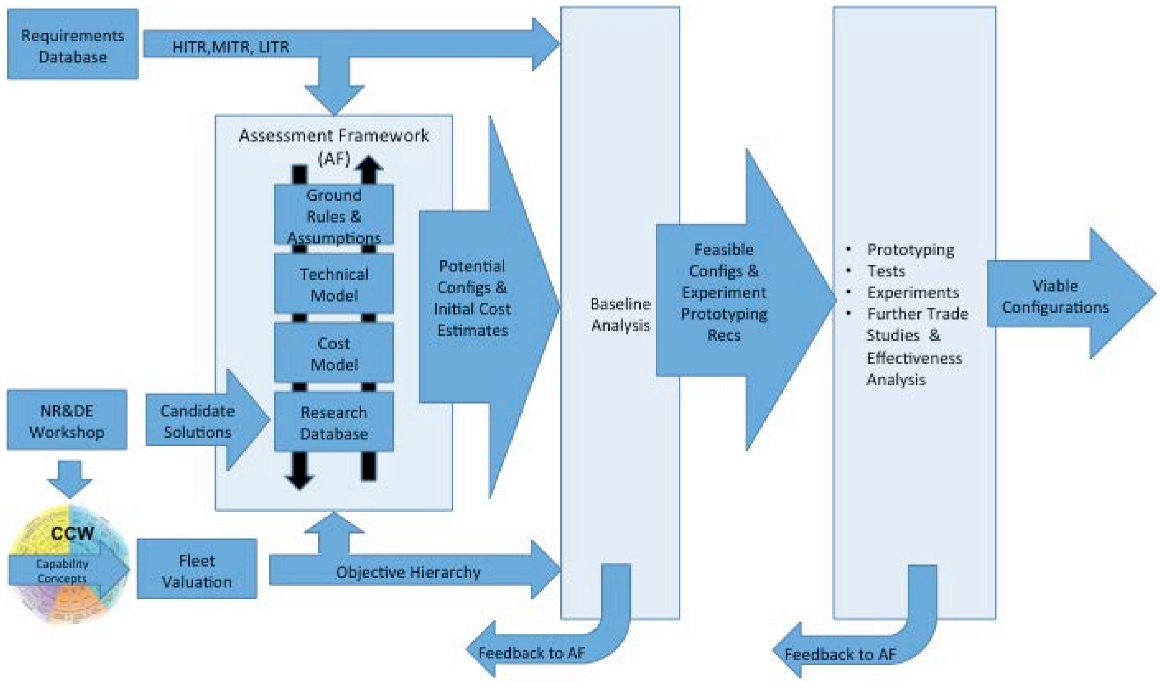

Figure 13. LDUUV SBD Scope of Steps. Source: Hardro (2016, 2).

SBD is an intricate process and takes a great deal of commitment and resources to initiate; this will be apparent when working through this scope of steps.

Examining Figure 13, one can see that the implementation process revolves around the Assessment Framework (AF). The AF is a framework used by decision makers and analysts to integrate their cost and technology models, execute them, and visualize the results. This framework enables linkages between not only evaluation models, but databases to continue to pull the most relevant and newest technical data from. The AF is composed of four distinct modules: Ground Rules & Assumptions, Technical Model, Cost Model and the Research Database. The Ground Rules & Assumptions module sets the rules for the AF. The module defines the assumptions, reasoning, and engineering judgment used to bind the integrated framework.

The Technical Model is the tool used to evaluate different system or subsystem concept performance based on the technical parameters of the components. If considering emerging technologies, there needs to be a methodology to capture risk associated with certain technology readiness levels. The Cost Model determines life cycle costs of

systems or subsystems in terms of cost ranges. The Research Database looks similar in format to a Work Breakdown Structure and breaks down systems and subsystems to a low enough level to list the performance and technical characteristics. Continuously populating this database with new data, it becomes the building blocks for the design space with the AF. This data feeds the cost and technical models for further analysis.

The output of the initial AF run is a set of potential configurations, or the first round of solution sets, while a more detailed analysis will start to pare down the solution sets further. Each one of these modules requires careful integration to connect, formulate, and present the data in views so that the decision makers and stakeholders can make informed conclusions. Choosing the correct tools to evaluate the problem, integrating the results from different models, and displaying the solutions comprehensively are challenging tasks.

There are other influences to the considerations of the first solution sets and those are the outputs of the Requirements Database (RD) analysis and the Fleet Valuations (FVs). The RD is the mirror image of the CDD, but each of those capability requirements are ranked via input from the Stakeholders into high impact, medium impact, and low impact tradable requirements (HITR, MITR, and LITR). This ranking or “binning” of requirements puts more focus on the HITR when utilizing the AF. There is an emphasis on understanding how the requirements correlate and trade, and therefore accounted for in the excursions of the AF.

The FVs are another major influence into the AF. The valuation is a manner of gathering Fleet input and priority into what capabilities are important when running LDUUV missions. During the composition of this report, the design team held a one-day workshop with given mission scenarios to gather Fleet priority. Figure 14 depicts the CCW, a tool used to gather the Fleet input. The CCW is very similar to the Small Surface Combatant CCW. Both focus on the major capabilities of their respective systems.

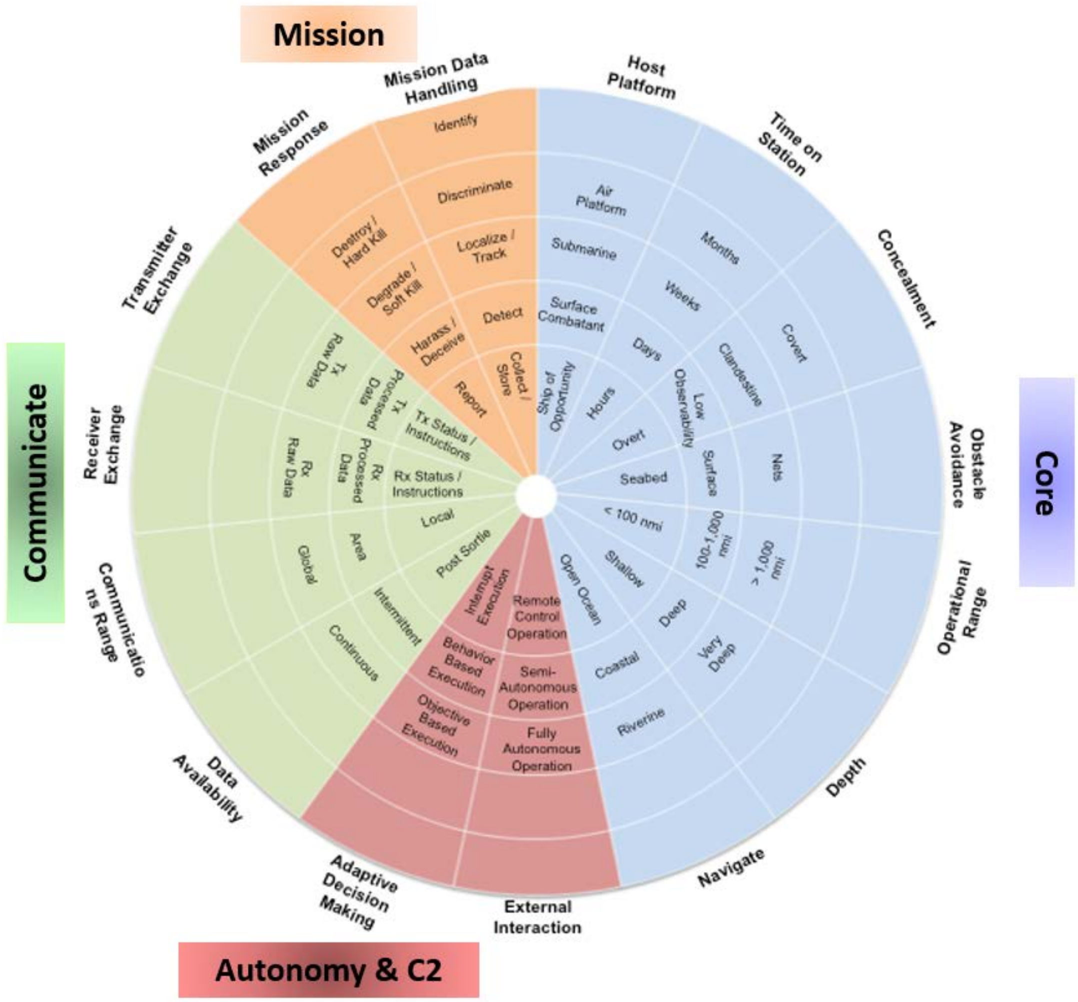

Figure 14. Capability Concept Wheel for the LDUUV. Source: Hardro (2016, 5).

This CCW is still a draft and will evolve as more input is received from the NAVSEA O5 (Naval Systems Engineering Directorate) technical community. The wheel represents four capability concepts: Communicate, Autonomy & Command and Control (C2), Mission, and Core. From there the CCW partitions down into capabilities and then to capability increments. For example, within the capability concept "Autonomy & C2," Adaptive Decision Making and External Interaction are the capabilities. Within the capability "External Interaction," moving from lowest capable to highest (inside to outside of circle), Remote Control Operation, Semi-Autonomous Operation, and Fully Autonomous Operation are the capability increments. The CCW then garners input from the Fleet through these capabilities that should encompass an entire LDUUV unit. The

output of the workshop is a hierarchy listing of capabilities in order of importance; this information feeds the AF to add another variable to the decision-makers view when choosing the best solution.

After populating the AF data, the designers generate the first set of potential configurations through the inputs and relationships built, tools chosen, and components integrated. According to Figure 13, LDUUV Scope of Steps, this is the "Baseline Analysis" (Hardro 2016, 2). After the initial determination, the design space narrows by adding more fidelity to the design by means of constraints, more defined requirements, engineering judgment, and cost analyses. They then produce detailed models and analyze an integrated logistics support system. This more detailed analysis generates a list of feasible configurations and from there, low-fidelity subsystem prototyping, tests, experimentation, and further detailed analysis take place to demonstrate a list of viable configurations. The result is the elimination of infeasible sets, creating a global solution and presenting the well-informed customer with more than enough detail to make a decision.

The LDUUV, being in its infancy stages of the SBD implementation process and procedures, continues to adapt to some flux, as can be expected, as much more detail and fidelity emerges over the course of the project. Most of the personnel working the SBD methodology are new to it, which presents a learning curve in the process, leading to even more fluctuation. It is apparent from the other case studies that there is no right way to implement SBD. That sort of advantage is beneficial if the team has experience using the process. To become more proficient with this methodology, the acquisition corps needs to produce guidelines and assumptions for how to execute and leverage the process. There is also a need for tools and templates to build certain SBD products such as a resource database or a capability concept wheel to provide repeatability and stability, as well as support documenting and applying lessons learned across the DOD community. The high level SBD Scope of Steps took two months to set up and since its inception, the tools utilized for the technical and cost modeling still not finalized. The CCW is on its third month of development and is still a draft. Changes to the CCW continue as more high-level input arises. The biggest challenge so far is not the

engineering behind SBD, but the administrative burdens in front of it, though stakeholders approve and progress moves forward on these products and processes. The smaller issues are the lack of experience utilizing SBD and the amount of legwork needed to initiate the SBD process (i.e., AF). As heard in an undisclosed meeting, VADM Johnson, the principal Military Deputy for the Assistant Secretary of the Navy for Research, Development, and Acquisition, once said, “don’t cost us out of the business.” The administrative and oversight burden has potential to do just that.

E. NAVAL SURFACE WARFARE CENTER CARDEROCK DIVISION POINT BASED DESIGN AND SET BASED DESIGN COMPARISON

The basis for the following case study is the slide presentation entitled “Engineered Resilient Systems for Ship Design and Acquisition” by MacKenna and his co-authors (2014). This presentation describes the results of a three-month design exercise to compare and contrast the application of PBD and SBD methodologies at Naval Surface Warfare Center Carderock Division.

They divided the employees at Carderock into two separate design teams, a PBD team and a SBD team. Both teams were tasked to further develop a provided baseline ship design with each to deliver a final ship design using their respective design techniques. They evaluated the designs for cost, effectiveness, and risk throughout the exercise. The exercise was intended to compare the resulting designs and lessons learned of using PBD versus SBD methodologies. During the study, the team introduced two sets of requirements changes and a mid-life system upgrade to determine how resilient the design process was and how it could adapt to the changes (MacKenna et al. 2014).

One significant finding from the study as presented by MacKenna and his co-authors (2014) was SBD’s effect on projected cost. At the beginning of the SBD execution, the design space is broad, and as a result, there was a wide range of estimated costs, representing the various potential ship design alternatives (2014). As the design space narrowed, the range of cost estimates narrowed. Figure 15 depicts this narrowing of the predicted cost estimates as percentage of baseline ship design cost estimate versus time for both the PBD and SBD designs.

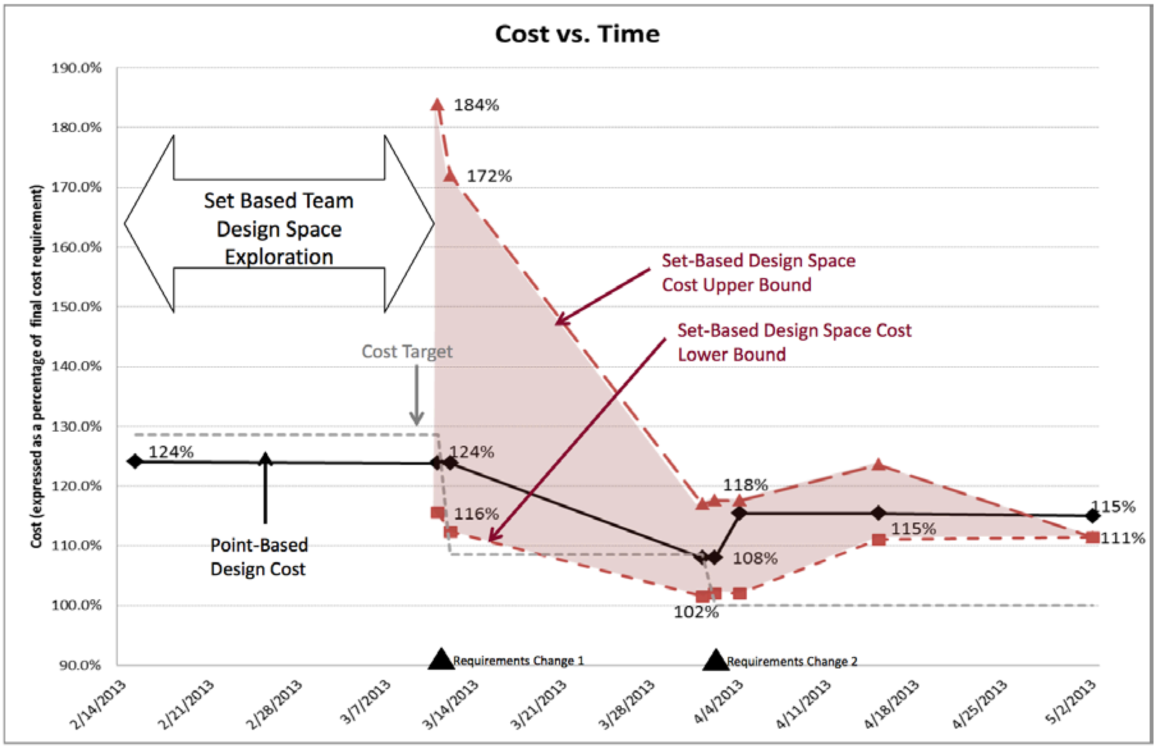

Figure 15. Cost as a Percentage of Baseline vs. Time. Source: MacKenna et al. (2014, 14).

The black line indicates the cost estimate for the evolving PBD solution, while the dashed red lines are the upper and lower bounds of the cost estimate range for the set of possible solutions the SBD team considered. Initially, during the design space mapping, SBD did not have established cost estimates as they explored the design space (MacKenna et al. 2014). The Requirements Change 1 came about in the middle of March 2013. At this time, the two teams reduced the estimated cost for their systems to just above the ship baseline. Requirements Change 2 arose in early April; this increased the projected cost for the PBD to 118 percent of baseline and the SBD range to 111–122 percent. The change forced rework in the point-based team's design, while the requirements change actually assisted the SBD team to eliminate infeasible solutions and helped reduce the design space (MacKenna et al. 2014). At the conclusion of the study, the resultant SBD solution was 4 percent cheaper than the PBD solution, at 111 percent and 115 percent respectively, of baseline ship cost.

Table 5 summarizes the Carderock design teams' experience applying the two methodologies (MacKenna et al. 2014, 16).

Table 5. PBD and SBD Comparison. Source: MacKenna et al. (2014, 16).

Point-Based Design	**Set-Based Design**
Design decisions largely driven by the designer's preference	Design decisions were driven by design/ analysis data, with each design decision formally documented
Design Decisions that were made early were largely set through the process. (ship sizing and system architectures)	Decision space was open until the end of the design process. Subsystem design was done before the ship was sized, ship sizing was one of the last steps
Design progressed rapidly, with iterations on detailed analysis happening early	Design progressed slowly at first, with significantly more work done up front, with lower fidelity tools, to reduce the design space to a point where more detailed analysis could be performed in an economical manner
Requirements change caused significant rework	Requirements changes caused no rework, and actually facilitated the set reduction process
As cost requirement decreased during the experiment, there was not much flexibility to adapt. Without exploration of the design space, the point based team had to guess how to achieve cost reduction	Set based process provide the team with robust information to do MOE versus aggressive cost goal tradeoffs
Resulting design: high performance, complex, high risk design with lower reliability	Resulting design: high performance, simple, low risk, and higher reliability

The comparison displays some of the key advantages of utilizing SBD. The SBD team kept the design space open until the end of the design period. As a result, the SBD team adapted quickly to the requirements changes without the significant addition of increased cost. Their design was very analysis oriented, using established tools to analyze the design space versus the designers' preference in the PBD design. In the end, the SBD was a simpler design with lower cost and risk.

F. CASE STUDY CONCLUSIONS

The case studies presented in this chapter provide insight to how DOD utilized SBD. The most important feature is the lack of similarity of the implementation process amongst the case studies; the absence of guidelines allows tailoring SBD to the specific needs of a program. There are, however, generalities or common themes selected to provide structure to the process, therefore presenting an opportunity to leverage these factors when making recommendations for acquisition tailoring. First, it is helpful to summarize the key attributes of SBD from the advantages and disadvantages standpoint; understanding these is paramount for choosing the acquisition strategy. Table 6 is a breakdown of some of the key SBD advantages and disadvantages.

Table 6. Advantages and Disadvantages of SBD.

Advantages
Establishes system design feasibility before commitment
Design development is not limited to a single solution
Enables parallel system level development with subsystem level development
Delays decisions on system requirements until trade-offs are further understood while continually promoting design discovery
Flexibility for requirements change
Concurrent discipline design development can take place by remotely dispersed design team
Enables rapid analysis of competing systems and design alternatives
Enables low risk and high reliability designs via eliminating infeasible solutions first
Cost commitments deferred until sufficient design detail permits selection
Longer period for stakeholder influence and feedback
Allows for design flexibility, reducing re-work and providing potential cost savings

Disadvantages
Higher initial costs upfront in the design process
Commitment of resources needed to build Assessment Framework and perform integration of SBD tools
Lack of education and experience from which to draw during execution and implementation of SBD.
No guidelines or assumptions for SBD process and execution
No instruction or guidelines for integration into DOD acquisition

There are multitudes of advantages, hence the popularity and the push to leverage this methodology. This and the previous chapter discuss the first four advantages listed, which are the core benefits of SBD. Set Based Design allows design feasibility before commitment, does not limit design development to a single solution, condenses overall design development time through multiple parallel efforts and, most importantly, demonstrates fidelity in system requirements by delaying decisions until more is understood about the trade-offs (Byers 2016). These core benefits help enable the Fleet to receive rapid reliable delivery of advanced defense systems.

Other less touted advantages are in the remaining items listed. “Flexibility for requirements change” relates to the focus on delaying design decisions until better understanding requirements (Gray 2015). The analysis and the shrinking of the design space accept requirements changes to help further define the space. SBD allows for a greater period for evolving or changing requirements as compared to the point-based method; PBD lends itself to costly scope creep due to stress surrounding the requirements of the system. This advantage directly feeds “Longer Period for Stakeholder Influence and Feedback.” The postponing of design decisions allows the customer more flexibility to adjust requirements over a longer period. With the changing threats, operational environments, and advancing technologies, having this luxury is crucial in fielding the right system at the right time to meet the evolving need.

"Concurrent discipline design development can take place by remotely dispersed design team" is true and important because subject-matter experts and/or Integrated Project Teams can work remotely through different commands or in different geographical locations, which is often the case for a government-led systems integrator. The development of subsystems in parallel through SBD principles lessens the need to have the complete design team centrally located. A team of core system integrators, as well as the System Chief Engineer, will flow the subsystem design spaces into the analysis tools to neck down the solution space and provide feedback to the team on refinements (Sobek et al. 1999).

"Enabling rapid analysis of competing systems and design alternatives" is an advantage if the right analysis tools are available. This may not yet be the case for a majority of systems, though Naval Surface Warfare Center Carderock Division is working on a few for ship design practices (Gray 2015). Assuming these tools do exist, there is the ability to analyze millions of solution sets to support shrinking the design space at a rapid rate.

"Enabling low risk and high reliability designs via eliminating infeasible solutions first" is true because SBD analyses look at and remove infeasible design. Once the solution sets narrow enough, modeling and simulation, and prototype testing occur. This process naturally creates more robust and lower risk designs because instead of choosing a less effective design and refining it through iteration, the solution becomes apparent by eliminating surrounding solution sets.

"Cost commitments deferred until sufficient design detail permits selection" is a major advantage this entire process. As the system understanding matures and the infeasible solutions eliminated, the commitment of cost delays until the design converges to a single design solution.

The majority of disadvantages relate to the lack of experience and guidance regarding the SBD methodology and how to implement SBD applications into the DOD acquisition process. There needs to be a standard process to follow for implementation

and guidance detailing how best to implement SBD as not only a process but within the DOD acquisition framework; standardization is required.

"Higher initial costs upfront in the design process" and "Commitment of resources needed to build Assessment Framework and perform integration of SBD tools" are some harsh realities of SBD. Resource sponsors will have to consider the upfront costs to define the design space, generate the solution sets, determine feasibility, remove infeasible solutions, and converge on a set of more feasible solutions, based on capability needs, to prove out viability during prototyping. This will create an initial work bow wave to initiate the effort, which also means more resources and funding. The information such as costs, design parameters, risk, fleet value and technology maturation, needs to be concentrated for various families of systems to perform the analysis. The data gathering to support these systems is burdensome and time consuming. The integration of the database and analysis tools must occur for the AF, which is an analysis within itself, and the proper structuring is crucial because it is the weapon for defining and converging the solution sets.

Prior to proceeding with SBD, decision makers should well understand the attributes described herein. Although beneficial, the methodology does have its limitations, but the promising news is that some of the concerns are avoidable. The list above helps identify the generalities among the case studies for SBD, as defined below.

Using SBD should be faster. The first three case studies all implemented SBD to get to a solution faster mainly due to schedule constraints, for which they succeeded utilizing this methodology. The word choice "should" was thoughtfully used because, as learned from the LDUUV case study, which is the furthest along in the acquisition process, the approval processes and oversight required via the Department of the Navy *Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System* (SECNAVINST 5000.2E) caused schedule delays. The DOD acquisition process needs to be analyzed and tailored in order to take advantage of the positive SBD aspects.

Applying SBD methodically shrinks the design space by eliminating infeasible solutions in a step-like process. The case studies all went through steps to shrink the design space after discarding infeasible alternatives. As more fidelity develops, the design the space transforms. Knowing this, should design space reduction milestones be set and aligned with the different gates or milestones within the SECNAVINST 5000.2E? Some technical documents may permit reductions of the set prior to adding more fidelity. There is a balance of procedure, stakeholder input, and maintaining a rapid prototyping methodology to consider when addressing this question.

The system development activity can leverage SBD in different capacities and at different times within acquisition framework. The LDUUV and the Ship to Shore Connector take place after Milestone A. The other two case studies are feasibility studies that occurred prior to Milestone A. Is the SBD methodology better leveraged in a study capacity or can it be just as successful implementing it through Milestone B and beyond? Should there be a best practice for this? When analyzing the acquisition framework, we make recommendations for implementing SBD as well as how to tailor the Gate criteria to amplify SBD’s return on investment.

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IV. TAILORING NAVY ACQUISITION FOR SET BASED DESIGN

Successful application of SBD in defense acquisition depends on several factors. This chapter explore these factors and how they may influence the use of SBD in program development efforts. These factors include:

1. The applicable defense acquisition directive and instructions
2. Whether the system being developed is hardware or software dominant and the acquisition model planned
3. The SBD tools available to the program,
4. If additional investment in tools could be required to execute SBD within the program,
5. Programmatic factors, such as the effect of delaying decisions and possible ways to communicate in sets
6. The use of prototyping in SBD

This chapter reviews potential acquisition scenarios. These scenarios provide two examples of how SBD could be used within the applicable Navy's acquisition instructions, and to highlight the process tailoring for future program managers to consider, when executing SBD acquisition program. The review begins with a look at applicable instructions.

A. REVIEW OF APPLICABLE DEFENSE ACQUISITION DOCUMENTS

SBD has been in practice in industry for some time. However, the application of SBD methodology in design is new to DOD acquisition programs and projects. Defense acquisition policy is set forth in Department of Defense Directive (DODD) entitled *The Defense Acquisition System* (DODD 5000.01) by the Under Secretary of Defense for Acquisition, Technology and Logistics (USD(AT&L)). It states "the primary objective of Defense acquisition is to acquire quality products that satisfy user needs with measurable improvements to mission capability and operational support, in a timely manner, and at a fair and reasonable price" (2007, 3). Additionally, it directs acquisition to have flexibility, responsiveness, innovation, discipline, and streamlined and effective management. Under

innovation, it charges all acquisition professionals to "continuously develop and implement initiatives to streamline and improve the Defense Acquisition System" (2007, 3). USD(AT&L) specifically calls on Milestone Decision Authorities (MDAs) and Program Managers (PMs) to "examine and, as appropriate, adopt innovative practices (including best commercial practices and electronic business solutions) that reduce cycle time and cost, and encourage teamwork" (2007, 3). The study of SBD to improve the design processes used in defense acquisition directly supports this directive.

The incorporation of SBD within acquisition programs will likely require tailoring of existing processes and procedures. *Operation of the Defense Acquisition System* or DOD Instruction 5000.02 (DODI 5000.02) implements the DODD 5000.01 across the department. Like the DODD 5000.01, the DODI 5000.02 reiterates the authorization for MDAs to tailor programs to meet the DODD 5000.01 primary objective. DODI 5000.02 specifically authorizes MDAs to tailor regulatory and acquisition procedures as long as it is consistent with DODD 5000.01 (USD(AT&L) 2015). Therefore, any tailoring of processes, reviews, or procedures, to incorporate and take advantage of SBD, is authorized for responsible MDAs as they see appropriate.

B. FACTORS TO CONSIDER BEFORE SELECTING TO USE SBD

The impact of utilizing the SBD process will differ depending on several factors. This section identifies those factors to assist both the program manager and the lead systems engineer in determining if the SBD methodology is viable. DODI 5000.02 outlines six defense acquisition program models that offer baseline examples for defense programs. "Acquisition programs should use these models as a starting point in structuring a program to acquire a specific product" (USD(AT&L) 2015, 8). Figure 16 depicts a hardware intensive development program model, which is the typical model for most DOD acquisition programs.

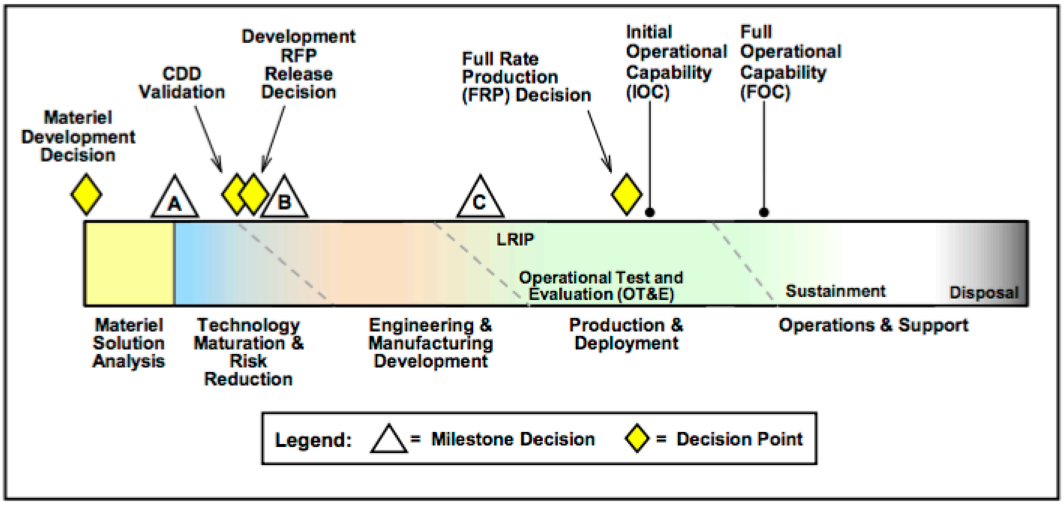

Figure 16. Defense Acquisition Program Model – Hardware Intensive Program.
Source: USD (AT&L) (2015, 9).

The program model contains a typical system life-cycle familiar to any systems engineering effort: requirements and product definition analysis, risk reduction, development, testing, production, deployment, and sustainment phases punctuated by major investment decisions at logical programmatic and contractual decision points (USD(AT&L) 2015). Each decision point (Materiel Development Decision (MDD), CDD Validation, Development RFP Release Decision, Full Rate Production Decision, Milestone A, Milestone B, Milestone C) provides the MDA with the ability to review both the programmatic and technical status and risks prior to proceeding to the next acquisition phase.

Table 7 lists the six DODI 5000.02 Defense Program Acquisition Models. The first four models are the baseline models, while Models 5 and 6 are hybrid models for programs that have hardware and software intensive programs respectively. Each model contains the same DOD phases and decision points, but the software models add software build options in between decision points.

Table 7. Defense Program Acquisition Models.
Source: USD (AT&L) (2015, 9).

Model 1	Hardware Intensive Program
Model 2	Defense Unique Software Intensive Program
Model 3	Incrementally Deployed Software Intensive Program
Model 4	Accelerated Acquisition Program
Model 5	Hybrid Program A (Hardware Dominant)
Model 6	Hybrid Program B (Software Dominant)

Figure 17 depicts the accelerated acquisition program model. In this model, one can see that milestones A and B are put together resulting in one preliminary decision point before getting to the milestones.

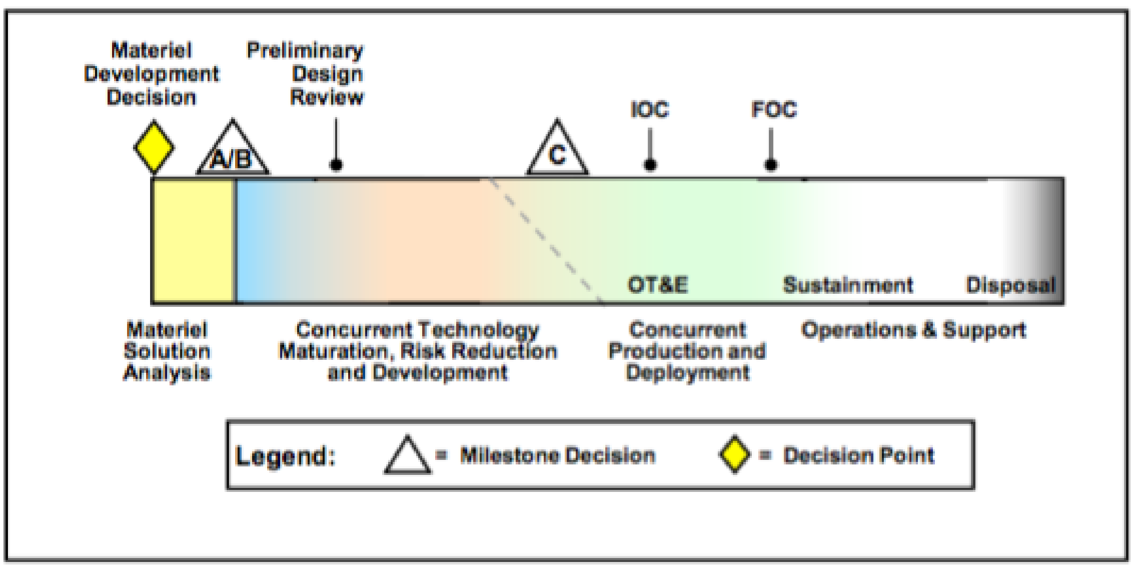

Figure 17. Accelerated Acquisition Program Model. Source: USD (AT&L) (2015, 13).

The hardware intensive program model follows the traditional DOD acquisition approach and can easily incorporate SBD. The chapter expounds upon this approach

later. The accelerated acquisition program focuses on accelerating the program to deliver a system on a reduced schedule. The accelerated acquisition program model combines Milestones A and B and only has the material development decision point. SBD complements both the hardware intensive program model and the accelerated acquisition program model.

SBD may be an approach for the Accelerated Acquisition Program model although the DOD acquisition implementation may require tailoring due to the shortened acquisition phases. The Accelerated Acquisition Model reduces the number of decision points/Milestones to three: the MDD, a combined Milestone A/B, and Milestone C.

The Defense Unique Software Intensive Program and the Incrementally Deployed Software Intensive Program are software intensive program models, while Hybrid Program B (Software Dominant) is a software dominant hybrid model. Figure 18 shows an example of an incrementally deployed software intensive program model.

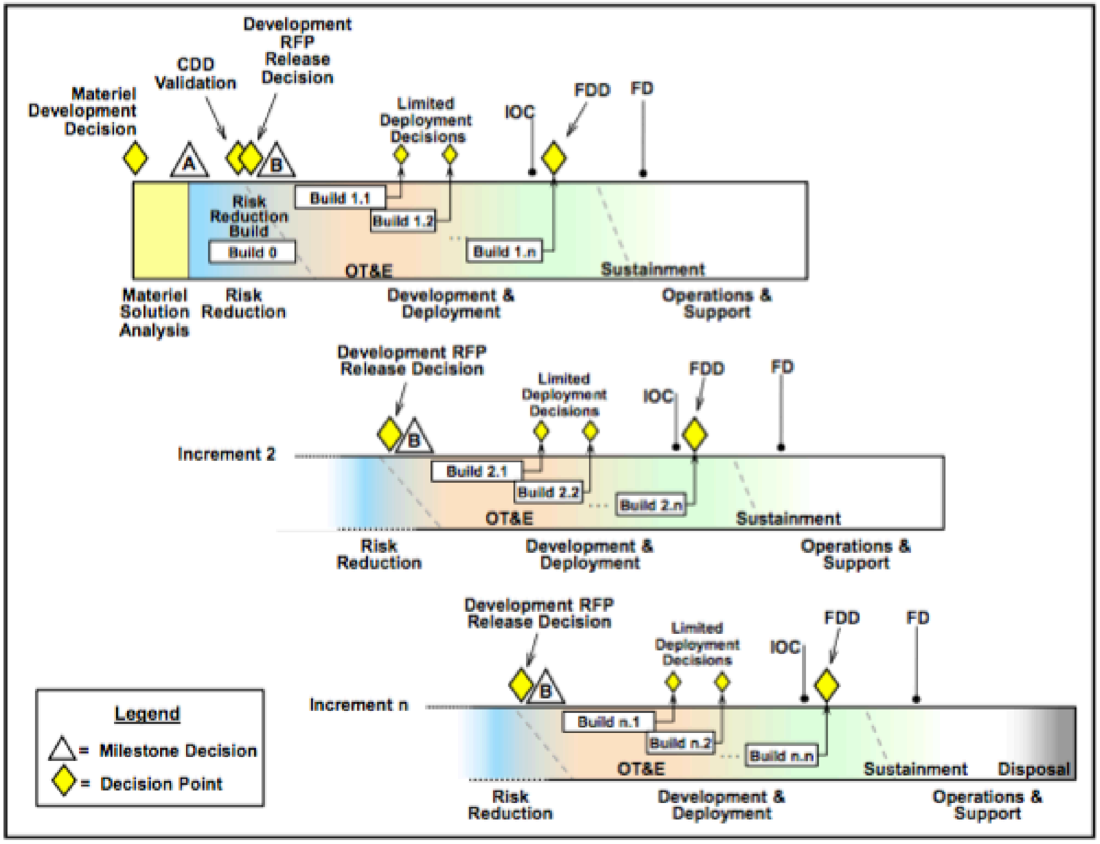

Figure 18. Incrementally Deployed Software Intensive Program. Source: USD (AT&L) (2015, 11).

This shows how the acquisition cycle breaks down into increments focused on software capability. This does not fall in line with the SBD methodology of delaying decisions until feasibility is known and instead focuses on an incremental approach that builds on the previous version, qualities of PBD. Current software acquisitions focus more on the agile development process, which prioritizes efforts in software builds, versus delaying cost commitments. According to the Project Management Institute, agile software development focuses on quickly producing prototype products to rapidly solicit feedback from stakeholders, “for early, measurable (return on investment) ROI through defined, iterative delivery of product increments” (2016, 1). Like SBD, these software development practices emphasize prototyping. However, agile software development progressively elaborates via accelerated PBD increments, not by maturing solution sets as described in the SBD principles (Project Management Institute 2016). Perhaps the best

strategy for the application of SBD in software activities is to apply SBD principles to narrow the design space of the feasible software system performance and functional requirements. To aid in the elimination of infeasible alternatives, software prototypes should employ agile software fast incremental cadences to obtain rapid feedback from stakeholders. Therefore, the use of SBD in software intensive systems is limited. The focus of SBD in DOD acquisition should be on hardware intensive systems in which requirements ranges and tradeoff curves are easily defined and for which there are more defined tools available for analysis among solution sets.

When determining whether to employ SBD or not, one must consider how far along the system development is and at what point is the program in the acquisition life cycle. Programs must ensure that SBD starts early on when design trade space is still available. From the case studies reviewed in the previous chapter, all of the programs utilized SBD early in program acquisition. The Ship to Shore Connector program utilized SBD during preliminary design while the ACV and the Small Surface Combatant utilized SBD for an AoA. The LDUUV planned to use SBD through the preliminary design stage but the effort has not begun yet. Conducting SBD late in the program life cycle, post Critical Design Review (CDR), will not provide as much value since the program is already committed to the design, thereby preemptively eliminating the number of feasible alternatives before leveraging the benefits of SBD.

The complexity and level of integration in the program are also important to account for when considering SBD. The Ship to Shore Connector, Small Surface Combatant, ACV, and the LDUUV case studies are all programs that deliver the entire system, providing full control to the program manager. The system arrives in one piece and the program has oversight over all the internal interfaces. SBD might not work as well for a single system that is part of a greater system of systems (SoS) with multiple programs involved. A complex SoS with multiple interfaces may require locking down certain specifications earlier in the acquisition life cycle to ensure proper integration, limiting the use of SBD. For example, the Preliminary Design Review typically results with drafts of the interface control documents, finalized by the CDR. This narrows the trade space, limiting the value SBD may provide. The practical application of SBD will

vary among subsystems as well. In Toyota's approach, designers decide on transmissions very early due to the complexity and costs, while they leave open decisions on exhaust system designs until the final specification (Ward et al. 1995).

Hardware specific programs that are early in the life cycle leverage SBD the best. Programs with few complex interfaces or well-defined interfaces are preferred. All of these factors maximize the application of the SBD principles to get the full benefit from a typical point based design approach.

C. SBD TOOLS

Proper SBD analyzes variables to explore trade-offs, review multiple alternatives, look for intersections of sets, and narrow the sets in a timely manner to meet design schedules. In order to conduct this analysis, proper tools are required to inject and analyze these requirements and metrics. Without proper tools to conduct the analysis, the trade space cannot be analyzed effectively. Both the Small Surface Combatant and the ACV utilized a DOORS database and the Framework for Assessing Cost and Technology (FACT) systems engineering toolsets. The teams entered cost and technical parameters into these tools, which automate calculations for the various studies (Burrow et al. n.d.). NAVSEA has developed several tools to analyze complex design issues, to include the Advanced Ship and Submarine Evaluation Tool (ASSET), in order to conduct total ship synthesis, and the Leading Edge Architecture for Prototyping Systems (LEAPS), to integrate a variety of analysis tools in a common data environment (Kassel 2012). NAVSEA continues to improve incrementally both ASSET and LEAPS in order to improve their ship synthesis capability. NAVSEA has teamed up with the Office of Naval Research (ONR), the DOD High Performance Computers Modernization Office (HPCMO), and PEO Ships on the Computational Research and Engineering Acquisition Tools and Environments (CREATE) program to take advantage of the modern increases in computational power to develop these toolsets (Kassel 2012). For NAVSEA programs such as the LDUUV, the investment in these tools enables the program office to conduct parallel design efforts to determine the intersections of the design sets. Without tools, the

program would not be able to explore fully the design trade space while still meeting the program timelines.

The program needs to make a determination of the ability to tailor the tools for the program prior to utilizing a SBD approach. The tools available must be fully capable of taking in the various design variables and conducting the proper analysis to narrow the design sets. If tool investment is required for SBD, the program must determine the return on investment of these tools. A program will likely see greater reduction in cost by pursuing a SBD approach vice a PBD approach, as long as the enabling tools are readily available and the program can leverage the past investments of other organizations. If the use of SBD requires the creation of a tool, the program may not enjoy the cost and schedule benefits over a point based design method due to the time and money needed for tool development. If the program needs to create or update a tool, the cost and schedule to do this might make adopting a SBD approach less cost-effective.

D. PROGRAMMATIC FACTORS WHEN IMPLEMENTING SBD

Applying SBD to a program will incur different cost and schedule risks than a typical PBD solution. SBD focuses on delaying cost commitments until there is sufficient knowledge to make proper decisions. Figure 19 illustrates the effect of SBD on the design process. This is a similar figure to the one shown in Chapter II.

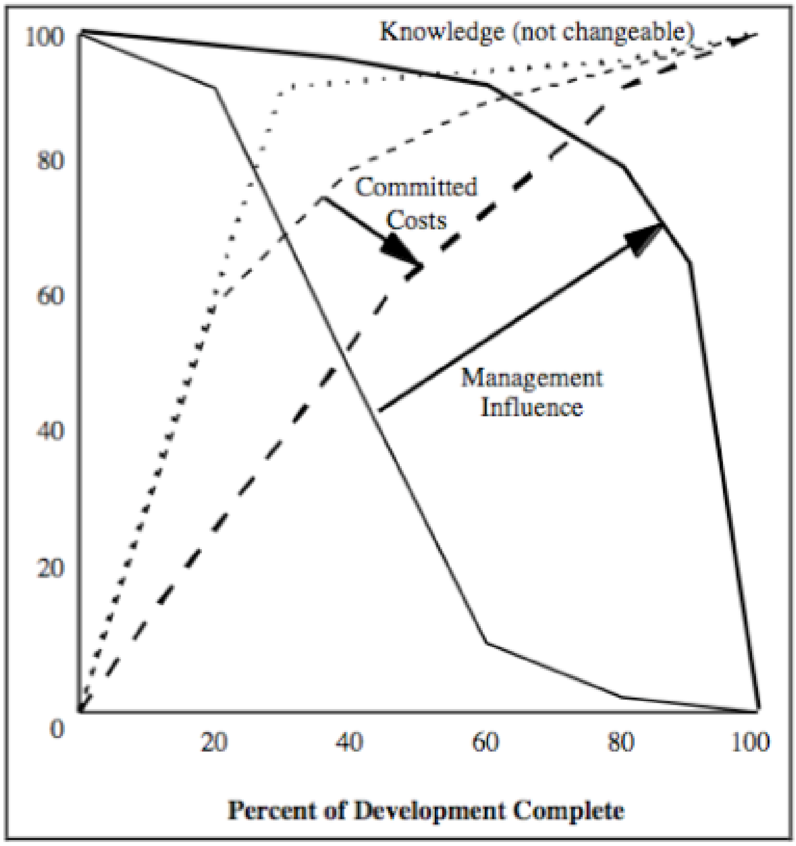

Figure 19. Impact of SBD on the Design Process. Source: Singer et al. (2009, 8).

The figure shows the percent of complete development versus the percent of costs committed. In a PBD, requirements and design are set early in the program life cycle. Program costs are committed as a result of making requirements and design decisions. As costs are committed, management influence decreases. In SBD, programs delay requirements and design decisions until they are fully understood. By delaying decisions, program managers reduce the risk of committing costs to the wrong solution and maintain the ability of management to influence the solution longer into the development cycle, thereby increasing the ability to adjust to mid-development requirements modifications. Set Based Design reduces both cost and schedule risks to the program to ensure that they design and deliver the right product (Singer et al. 2009). Program managers will still need to understand how implementing SBD will change the cost and schedule of a program.

To map properly the design space, SBD requires increased resources early in the program and carries multiple solutions forward, unlike the traditional PBD approach. A major tenet of SBD, SMEs derive multiple sets of designs in parallel, then systematically narrow them by identifying solution intersections. In the ACV case study, four teams worked in parallel to analyze requirements, effectiveness, trade space, and affordability to develop alternatives (Burrow et al. n.d.). The Small Surface Combatant conducted multiple parallel efforts to define mission areas, the requirement trade space, and the design efforts (Mebane et al. 2011). While the parallel efforts reduced the total schedule compared to a linear study, requisite resources increased to support multiple teams.

To determine if SBD can be employed effectively, time and manpower must be allocated to analyze and search for tools. Funding and time may be necessary to upgrade tools, which could delay the start of the SBD process to conduct tool development. Fortunately, in the area of ship design, NAVSEA previously invested in the ASSET, LEAPS, and CREATE tools. While NAVSEA has the infrastructure in place, the tools must be configured to support specific programs, and upgraded as innovative, more advanced analysis techniques arise. NAVSEA took advantage of investments from other programs funded by ONR and HPCMO. If another Systems Command (SYSCOM) is unable to leverage these investments, then it may require significant investment to conduct SBD, which a program manager may not have in his or her budget. Cost and schedule risks increase if the tool development does not mature quickly enough to support the program schedule.

SBD advocates for multiple prototypes. Prototyping can accelerate knowledge gain and reduce technical risk. It also increases the research and development costs versus baselines with minimal or no prototyping planned. While the case studies analyzed were requirements focused, Toyota is a proponent of prototyping and including suppliers in the SBD process. One Toyota exhaust supplier developed approximately 10 to 20 exhaust prototypes for each new Toyota car design (Ward et al. 1995). This was key in supporting the development of requirements and design of the overall system.

Set Based Design delays design decisions until the feasibility of potential solutions is established, enabling trade-off decisions between feasible solutions. Delaying

the decision-making until later in the program life cycle means that a majority of the decisions happen toward the latter end of the schedule. Though this helps improve confidence in the design decisions, there will likely be less slack in the schedule, causing problems if issues arise. Additionally, there is a risk to the schedule if one of the parallel efforts falls behind, resulting in higher cost and schedule risks for the dependent systems, which require interface with the system under development. Often in the DOD, the maturity of interfaces is the subject of review at various technical reviews and how detailed they appear in the appropriate interface control documents. Delays in design decisions may also delay finalizing these documents, causing a cascading delay to interfacing systems from finalizing their designs. Efforts should focus on defining interface control documents early enough to enable interoperability with dependent systems, however define them to be flexible enough to avoid rework once the design is finalized (e.g., providing extra discrete signals for growth, adopt robust protocol standards).

Finally, SBD advocates for more efficient communication among the stakeholders. There must be a consistent approach and communication plan to ensure all stakeholder expectations maintain alignment. Toyota was able to reduce both the frequency and duration of communication with their suppliers by employing SBD in parallel. However, Toyota was the lead organization and able to be directive to their suppliers. Employing SBD in DOD acquisition will require support from all levels of DOD organizations involved, though it is unclear if SBD can improve communication efficiency within the DOD. The organizational structure of stakeholders in many complex DOD systems is more horizontal than the top-down Toyota-to-suppliers model. Most technical communication in the DOD is via written specifications. The development of sets of detailed specifications for multiple alternatives is not practical. Toyota communicates via ranges to define the set of solutions (Sobek et al. 1999). The DOD could adopt a similar strategy of increased use of acceptable ranges in order to enable set-based communications. Additionally, the use of Model Based Systems Engineering (MBSE) as a SBD tool facilitates set-based communications.

The advancement of MBSE tools could improve future set-based communications. Modern MBSE system models consist of interactive databases of system requirements, attributes, and relationships (Vitech Corporation 2011). These models enable the generation of multiple views of system solutions to facilitate analysis (Vitech Corporation 2011). Potential solutions arise through the generation of a set of models. The maturation of a set of individual potential architectures would empower rigorous trade-off analysis to eliminate less desirable architectures and narrow the solution set as advocated in SBD.

E. THE USE OF PROTOTYPING TO SUPPORT SBD IN ACQUISITION

Rapid, developmental, operational, low fidelity, high fidelity, competitive: all represent adjectives the DOD uses to define prototyping strategies. The evolution of prototyping extends beyond buying down technical risk; it reduces programmatic costs, increases pace of development, supports maturing industrial technical competencies, and informs decision-making earlier in the acquisition process (Hencke 2014). As stated by Borowski, “Prototyping enables better acquisition outcomes by improving the reliability of available information” (2012, 1). Prototyping does not need to be a complex pre-production model; it can come in all forms such as a concept, subsystem, or end item. A prototype is a test article, “Paper studies estimate a technology’s capabilities, prototyping demonstrates those capabilities through testing. Test articles are designed, constructed, and tested to demonstrate the capabilities of some technology or system” (Borowski 2012, 1). Based on this understanding of prototypes, those used prior to Milestone B should be repetitive low-fidelity prototypes with short development timelines to inform early design decision-making. In fact, it is now a requirement to prototype prior to Milestone B. Per SECNAVINST 5000.2E, which “requires that the acquisition strategy (interpreted to mean technology development strategy for the Technology Development (TD) phase) for each major defense acquisition program provide for competitive prototypes before Milestone B unless the MDA waives the requirement” (2011, 2–17). It is important for the program to stay within budget and to use prototypes advantageously, in a cost-effective manner, to gain understanding, mature high-risk technologies, and determine the intersections of feasible solutions. The SBD methodology supports low-

fidelity (cheap) prototyping early and often, for a better understanding of the design space, while integrating at the intersections of solution spaces in order to narrow the set of solutions (Ghosh and Seering 2014).

As described by Ghosh and Seering, developing low-fidelity prototypes to support examination of requirements is one of the seven key characteristics of SBD (2014). SBD promotes the use of low-fidelity prototyping, but at some point, more fidelity emerges into the test articles to advance the design to a manufacture-able product.

Figure 20 demonstrates a good comparison between the Technology Readiness Levels (TRLs), acquisition framework, and two major classifications of prototypes, developmental and operational (Hencke 2014). Low-fidelity prototyping falls in the developmental category. TRLs 1–4, or the pre-concept and material solution phases, are the most appropriate phases to maximize the usage of low-fidelity prototyping during the SBD process. The pre-Milestone A activities align with defining the design space and adding fidelity to narrow the solution sets, or trade space, within the domain disciplines. Although TRLs 5 and 6 are still considered developmental prototypes, the demarcation between low-fidelity and high-fidelity should occur between Milestones A and B, during the technology development phase.

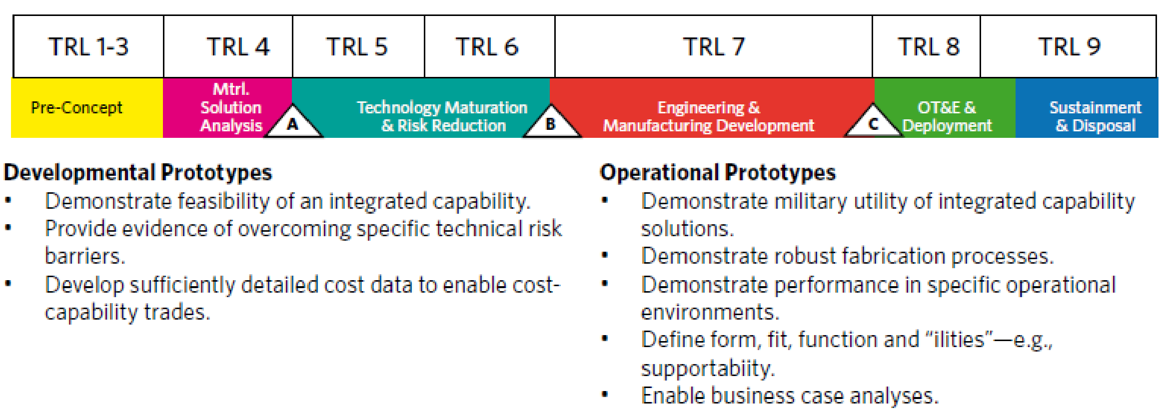

Figure 20. Prototyping TRLs within the Acquisition Framework. Source: Hencke (2014, 12).

For this analysis, assume the PDR occurs prior to Milestone B. The most important output of the PDR is the system allocated baseline. According to AcqNotes, the allocated baseline is the:

> Definition of the configuration items making up a system, and then how system function and performance requirements are allocated across lower level configuration items. It includes all functional and interface characteristics that are allocated from the top level system or higher-level configuration items, derived requirements, interface requirements with other configuration items, design constraints, and the verification required to demonstrate the traceability and achievement of specified functional, performance, and interface characteristics. (AcqNotes 2016)

There will be little trade space available after the allocated baseline is produced, meaning there will be minimal trade space left post-PDR. Therefore, to obtain that level of higher fidelity, more robust prototypes must be introduced into the technology development phase to either mature the critical technology or mature the system to demonstrate affordability. These higher fidelity prototypes will drive the SBD process and narrow the trade space to a minimum. These prototypes are the more enhanced, more capable developmental prototypes. Developmental Prototyping has a tipping point of diminishing returns; it will become uneconomical not to drive the design to the allocated product baseline, also known as the build-to specifications, which is the output of the CDR (AcqNotes 2016). Not all risk reduces and the detailed design remains on a strict schedule. In general, post PDR, one allocated system baseline should be carried forward to the begin preforming detailed design and use full-scale prototypes as needed to demonstrate in-situ, operational performance. Therefore, prototyping, especially at the low-fidelity level, is a key driver for the SBD process pre-Milestone B and will better promote trade-offs and the exploration of the design space.

F. SELECT DEFENSE ACQUISITION STRATEGY SCENARIOS

Tailoring of processes at the program level is how a POR incorporates and maximizes SBD into their program. Each program will likely have unique acquisition strategy considerations and applicable SYSCOM processes. Programs tailor the service-issued instructions as approved by their PM’s cognizant MDA. These service-issued

instructions provide additional detail on how to execute the DODI 5000.02 within their service. The Navy has issued guidance in the Department of the *Navy Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System* (SECNAVINST 5000.2E) instruction, which was signed on 1 September 2011. The document describes an overview of the Navy's acquisition management process including the 2-Pass/6-Gate DON Requirements and Acquisition Governance Process, illustrated in Figure 21.

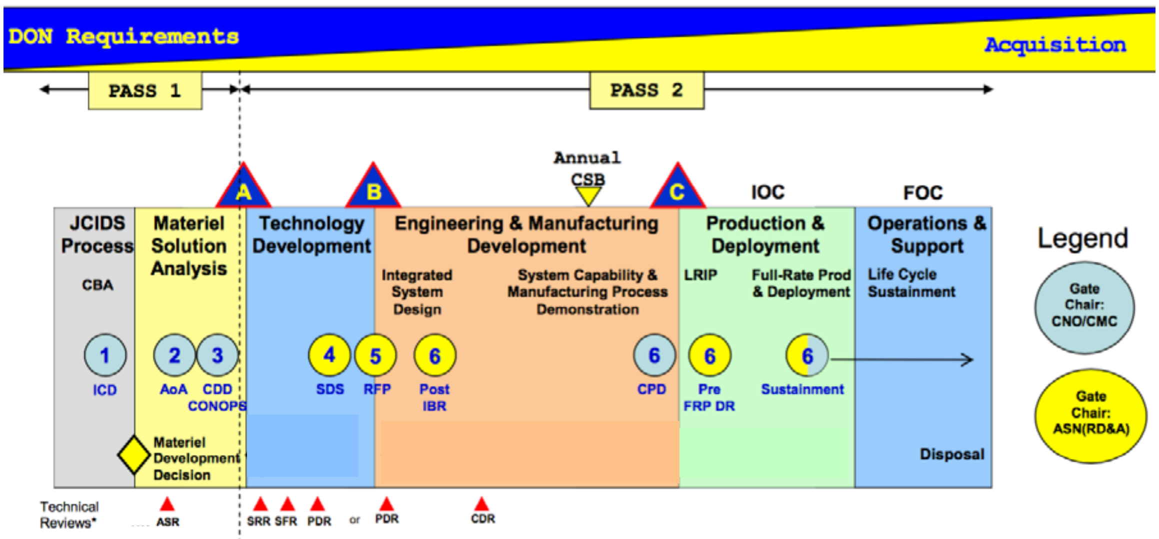

Figure 21. 2-Pass/6-Gate DON Requirements and Acquisition Governance Process. Source: ASN(RD&A) (2011, 1–60).

The SECNAV stated goal of the 2-Pass/6-Gate process is to "ensure alignment between Service-generated capability requirements and systems acquisition, while improving senior leadership decision-making through better understanding of risks and costs throughout a program's entire development cycle" (2011, 1–51). The 2-Pass/6-Gate process applies to all pre-Major Defense Acquisition Programs (MDAPs), all MDAP Acquisition Category I (ACAT I) programs, all pre-Major Automated Information System (MAIS) programs, all MAIS ACAT IA programs, and ACAT II (2011). The 2-Pass/6-Gate process has two major phases: Pass 1 and Pass 2. The Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) are the chairpersons

for Pass 1 reviews. Their designees lead these reviews via the R3B process. The R3B is "the Navy's 3- and 4-star forum for reviewing and making decisions on Navy requirements and resource issues (2011, 5). The SECNAV instruction establishes Pass 1 as the Navy's process to determine capability needs and encompasses the first three gates, focusing on documenting high-level requirements identified in the Joint Capabilities Integration and Development System process (2011). According to SECNAVINST 5000.2E, Pass 2 is led by the DON component acquisition executive (CAE), the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN(RD&A)), and includes Gates 4 through the Post-Integrate Baseline Review Gate 6, plus all follow-on Gate 6 reviews (2011). The process elicits and documents leadership program direction at identified decision points (2011). The difference in leadership between the two Passes is significant as it has implications on the level of design executed in Pass 1 versus Pass 2. A successful Pass 1 documents the capability need to enable the acquisition process executed in Pass 2 (2011).

The 2-Pass/6-Gate process builds on procedures developed to provide oversight of defense acquisition programs, which have traditionally been PBD style programs. Not until recently the DOD employed SBD, and to date, only in a handful of cases. That does not mean the processes are not effectively tailorable to provide oversight to SBD programs as well. To explore potential processes tailoring, consider the following two acquisition strategy scenarios.

1. Scenario 1

The government performs SBD from MDD until sufficient system requirements and system performance definitions are documented in a System Design Specification (SDS) as it is referred to in SECNAVINST 5000.2E. This is analogous to the FDD from the SSC case study; to inform a RFP to the defense industry to complete the detailed design (Mebane et al. 2011).

2. Scenario 2

The government performs SBD from MDD through system requirements definition, detailed design, and documents the system design in a Technical Data Package

(TDP) to enable a production RFP to a defense industry vendor or to produce Low Rate Initial Production (LRIP) items for testing and other entrance criteria to a Milestone C decision (ASN(RD&A) 2011).

Each of these SBD acquisition scenarios illustrates potential employment of SBD. The two scenarios show that the solution space narrows to different levels of detail, depending on the acquisition strategy and the handoff system development at different phases. Figure 22 illustrates how the SBD solution space reduces by eliminating the least desirable or infeasible solutions as more knowledge develops, resulting in the funneling effect which maps the broad design space on the left and then narrows the set of solutions as the program executes to the right, ultimately paring down to the final solution.

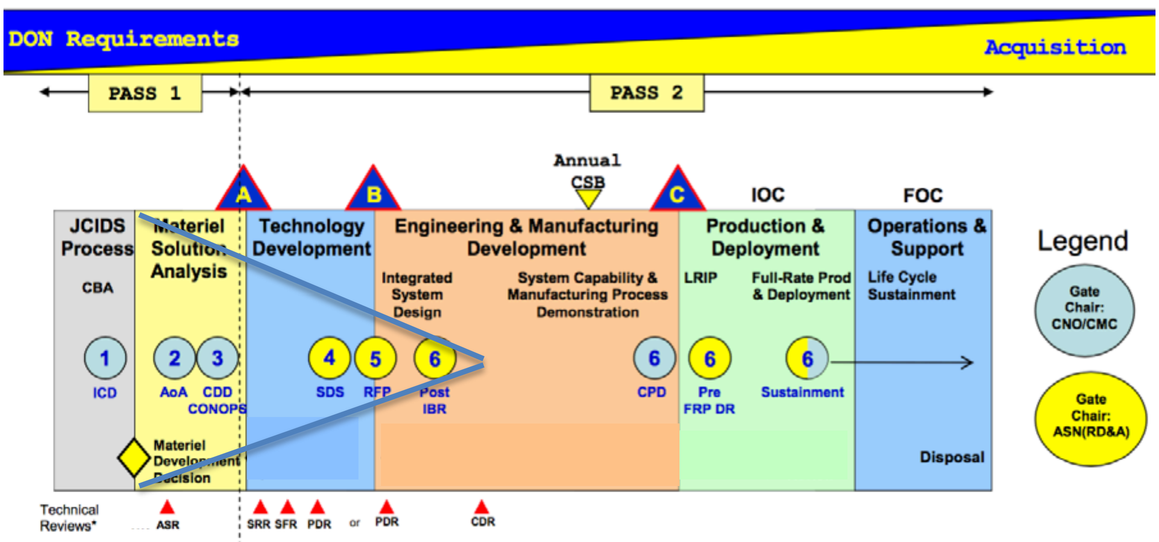

Figure 22. Solution Space Funnel Scenarios. Adapted from ASN(RD&A) (2011, 1–60).

G. PASS 1 AND GATE 4 IN A SET BASED DESIGN DEVELOPMENT

Due to the nature of Pass 1, the two scenarios will have a degree of commonality through Gate 3 and on to Gate 4 (first gate in Pass 2). Pass 1 establishes and approves high-level capability needs and transitions them to the CAE-led Pass 2 for the TD and Engineering & Manufacturing Development (EDM) phases (ASN(RD&A) 2011). To

facilitate this transition from Pass 1 to Pass 2, the team recommends specific SBD tailoring for Pass 1 and up to Gate 4. It is assumed that the selected scenarios will diverge from each other after Milestone A, at Gate 4, as they proceed through the Pass 2 process and are discussed in Sections H and I. The following is an examination of the common tailoring within the context of SBD, which applies to both scenarios introduced in Section F.

1. Gate 1 and the Materiel Development Decision (MDD)

Set Based Design influences the content contained within the Gate 1 entrance and exit criteria. One entrance criterion for Gate 1 is a completed Service review of the AoA Guidance (ASN(RD&A) 2011). If it has been determined that a SBD approach is desirable, the AoA Guidance should document it here. In the case of SBD, the Service review of the AoA Guidance should identify the boundaries for mapping the design space, satisfying the capability need documented in the ICD. The ACV case study presented in Chapter III is a good example determining the design space in a defense acquisition program. The ACV program identified the "big rocks" (Burrow et al. n.d., 3). The AoA Guidance would initiate the SBD process by identifying the "big rocks" as the tradable parameters, and more importantly, those that are not tradable to achieve the desired end-state. At this point, SBD methodology helps to explore the requirements space and evaluate the capability gaps with the Capability Based Assessment (CBA). To accomplish this, SBD evaluates Capability Concepts via techniques similar to the Capability Concept Bull's-eye chart and the CCW, described in Chapter III.

An application of SBD methodology at this stage will inform the MDD. The following is a list of the SBD principles presented as a review and a map to the relevant applications for this stage (Sobek et al. 1999):

2. Map the Design Space

a. Define feasible regions – Determine all feasible concepts that will satisfy the capability gap identified in the CBA.

b. Explore trade-off by designing multiple alternatives – Identify the "big rocks" and their relative importance to enable trade analysis and Capability Concept scoring.
c. Communicate sets of possibilities – Solicit feedback from Stakeholders and ultimately the selection of a Capability Concept by the MDA at MDD.

3. Integrate by Intersection

a. Look for the intersection of feasible sets – Mature the Capability Concepts and identify their intersections.
b. Impose minimum constraint – High-level Capability Concepts only at this point.
c. Seek conceptual robustness – Determine feasible concepts that satisfy the capability gap identified in the CBA.

4. Establish Feasibility before Commitment

a. Narrow sets gradually while increasing detail – Executed in concert with 1b, 1c, 2a, 2c, and 3c.
b. Stay within sets once committed – Aggressively apply configuration control to requirements baselines. Perform analysis to ensure all "big rocks" are traced to Measures of Effectiveness that support closing the identified Capability Gap.
c. Control by managing uncertainty at process gates – It is our recommendation that the above analysis should be performed to enable the selection of a Capability Concept(s) at the MDD.

The MDD is after Gate 1 and is "a review that is the formal entry point into the acquisition process and is mandatory for all programs. A successful MDD may approve entry into the acquisition management system" (Defense Acquisition University (DAU) 2016). Per SECNAVINST 5000.2E pre-ACAT I programs cannot combine the Gate 1 and MDD events (2011). Two different authorities chair these two events; for Gate 1, it is the CNO or CMC as appropriate, while the MDD is chaired by ASN(RD&A) (2011). By

prohibiting their combination, the process provides the opportunity to ensure alignment between these offices for ACAT 1 programs.

Gate 1 approves the AoA Guidance. This the logical starting place for the application of SBD. The AoA Guidance begins the SBD process to Map the Design Space, while the MDD approves the AoA Guidance and thereby documents the directions to execute a SBD approach for system development.

The use of SBD in defense acquisition is new and standard practices are still being defined. Therefore, it requires careful thought to inform stakeholders of the method of execution. Another tailoring recommendation is the development of the draft Systems Engineering Plan (SEP) early in the process. As written in the 2-Pass/6-Gate process, the draft SEP is an entry criterion to Gate 3 (ASN(RD&A) 2011). However, given direction from the MDD to proceed with a SBD approach, the draft SEP could and should start prior to Gate 2, in order to provide a basis for communicating the SBD execution to inform stakeholders.

5. Gate 2

Progressing further down Pass 1, we examine Gate 2. It is evident that the Alternative System Review (ASR), an entrance criterion for Gate 2, should be tailored for SBD. According to the Defense Acquisition Guidebook, the ASR facilitates communication among end user and defense acquisition stakeholders to enable the development of a draft performance specification (DOD 2013). In a PBD approach, once the AoA analysis is complete, the ASR serves to review the results and select the preferred alternative (DOD 2013). Additionally, this meets the “preferred alternative identified,” as a Gate 2 entrance criteria (ASN(RD&A) 2011, 1–61).

For a program employing SBD, the output of the ASR is the preferred Capability Concept if not already determined at MDD. While this is similar to “preferred alternative identified,” in the baseline SECNAV instruction, this tailoring provides recognition that the possible sets of system configuration alternatives remain in a development and evaluation stage (ASN(RD&A) 2011, 1–61). In the methodology discussed above, mapping the design space of Capability Concepts and identifying the preferred Capability

Concept, if not already been completed, occurs in preparation for the ASR. This decision point appears in Figure 23.

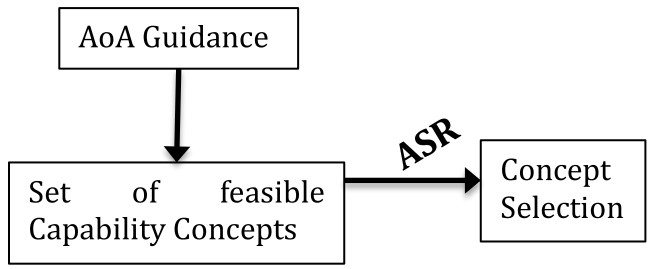

Figure 23. Flow of the Selection of the Capability Concept.

The ASR should focus on the big rock performance parameters that drive operational effectiveness. The output of the ASR is the performance parameters and the understanding of their relative importance in order to evaluate the set of possible system configuration alternatives. These performance parameters enable the reduction of the number of sets to a manageable number.

The SSC and ACV case studies both utilized SBD methodologies to improve their understanding of requirements. In the SSC program, the ICD, AoA, R3B disposition, technical data from the legacy system, and other lessons learned formulate the FDD. The FDD is a "set of operational requirements and derived parameters used to initiate the design effort" (Mebane et al. 2011, 83). In the ACV study, the comparison of the requirements occurred via trade-off analyses with the big rocks. Therefore, the output of the ASR could enable the development of the FDD Development Plan and a draft FDD that elaborates performance needs of the system to meet operational capability gaps stated in the ICD. Figure 24 depicts a diagram of the SSC Specification Tree and traces these source documents to the FDD. The big rock performance parameters facilitate trade-off curve development to reduce the number of sets of feasible system configuration alternatives and define the FDD. The draft FDD is refined in parallel with the CONOPS and CDD.

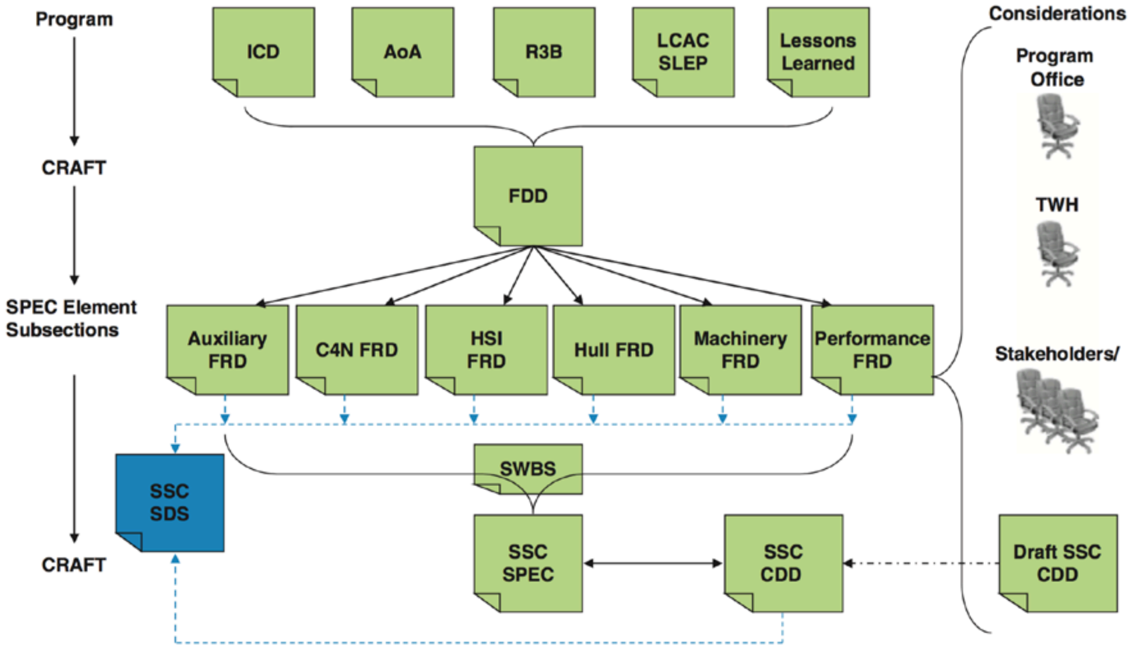

Figure 24. Ship to Shore Connector (SSC) Requirements to Specification Trace
Source: Mebane et al. (2011, 83).

6. Gate 3

Entrance criteria for Gate 3 also requires tailoring. Currently, the entrance criteria includes a completed service review of the CDD and CONOPS, and a draft SDS Development Plan (ASN(RD&A) 2011). Keeping with the development of a FDD, the FDD Development Plan should describe how the subsystem FRDs would be matured (Mebane et al. 2011). In the SSC article, Mebane and his co-authors describe the FRDs as "evolving set(s) of assumptions and potential requirements that further defined the element trade space and ultimately constrained element-specific requirements" (2011, 83). Analysis of big rock performance parameters can eliminate the infeasible sets of system configuration alternatives, in order to refine the list of assumptions for each subsystem and further mature the FRDs. The SBD principles are presented once again with example ways the methodologies apply to the development process going into Gate 3 (Sobek et al. 1999):

7. **Map the Design Space**

a. Define feasible regions – Determine feasible system configuration alternatives that will satisfy the FDD performance, that is the set of various subsystem alternatives and begin documenting subsystem performance and performance trade-off curves.
b. Explore trade-off by designing multiple alternatives – Identify derived subsystem performance ranges based on the Big Rock Performance Parameters trade-off analysis and their impact on system level performance to enable trade analysis and subsystem alternative scoring.
c. Communicate sets of possibilities – Solicit feedback from stakeholders and document in the FDD and draft FRDs.

8. **Integrate by Intersection**

a. Look for the intersection of feasible sets – Mature the draft FRDs and identify the intersections of feasible sets, eliminating infeasible sets.
b. Impose minimum constraint – Focus on the identification of derived subsystem performance parameter ranges to enable future trade-offs.
c. Seek conceptual robustness – Identify system configuration alternatives that are not conceptually robust for possible elimination from the set of considered solutions.

9. **Establish Feasibility before Commitment**

a. Narrow sets gradually while increasing detail – Executed in concert with 1b, 1c, 2a, 2c, and 3c.
b. Stay within sets once committed – Maintain traceability of derived subsystem performance ranges and functional allocations to Big Rock Performance Parameters and the CDD. No new system-level performance thresholds, focus is on getting the CDD approved. Any new user desires should be identified and prioritized for future increments.

c. Control by managing uncertainty at process gates – The application of these methodologies should result in the final set of FRDs, which are the basis of the SDS to be approved at Gate 4.

10. Gate 4

The purpose of the Gate 4 review is to approve the SDS and assess program affordability (ASN(RD&A) 2011). Major entrance criteria include the approved CONOPS, CDD, and SDS signed by the PM, responsible SYSCOM Chief of Engineering, and the resource sponsor (ASN(RD&A) 2011).

The SDS under consideration for approval at Gate 4 consists of the finalized FDD and FRDs. To arrive at this, the scope of materiel solution space reduces significantly, beginning from sets of Capability Concepts prior to MDD and followed by the selection of one Capability Concept at MDD. That concept is investigated by considering sets of system configuration alternatives (variations of subsystem configurations to meet mission requirements in the final CDD and traced to system level performance documented in the FDD). The CDD and CONOPS are approved at Gate 3 (ASN(RD&A) 2011). As the set of system configuration alternatives reduces, the FRDs become more concrete. Then, based on the work of Mebane and his contemporaries, "the requirements in the FDD and FRDs were subsequently mapped to their respective SWBS area to become the draft specification for SSC" (2011, 83). The draft specification is the draft SDS and consists of the final system-level FDD and subsystem-level FRDs.

H. ACQUISITION STRATEGY SCENARIO 1

Scenario 1 – The government performs SBD from MDD until sufficient system requirements and system performance definition are documented in a SDS. This allows a Gate 5 review to approve a RFP to defense industry to complete the detailed design, LRIP, and testing to inform a Milestone C decision. The natural progression of the system under development, after the approval of the SDS, is the development of the PD (NAVAIR 2015). The PD includes the Allocated Baseline (ABL) and obtains approval at Preliminary Design Review (PDR), (NAVAIR 2015). It is important to understand that the SDS does not include the complete set of required information and documentation for

the PDR Systems Engineering Technical Review (SETR) (NAVAIR 2015). Additionally, a combined System Requirements Review (SRR) and System Functional Review (SFR) during FDD and FRDs development is prudent to ensure no programmatic elements are overlooked and all logistical elements are addressed (NAVAIR 2015). The combination of these events is a significant tailoring, however, one that is appropriate given the development of the FDD and FRDs accomplishing the system and functional requirements derivation that are the focus of the SRR and SFR reviews. The combined SRR and SFR represent the control gate to select the preferred subsystem configuration of the possible set of feasible subsystem configurations. Figure 25 builds on flow diagram introduced in Figure 23 to illustrate these decision points.

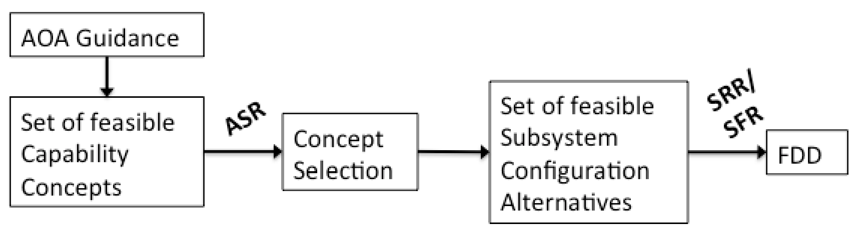

Figure 25. Flow of the Selection of the Subsystem Configuration through SRR/ SFR.

The specifications defined in the FDD are allocated to the respective FRDs. A draft FRD is therefore the set of possible subsystem configuration design solutions to meet the requirements allocated to a particular subsystem. The tradeoff analysis and elimination of infeasible alternatives narrows the design space of each of the individual FRDs. The FRDs mature as the final subsystem solutions emerge and the final FRDs gain approval at the PDR. Figure 26 depicts the decision flow to this point.

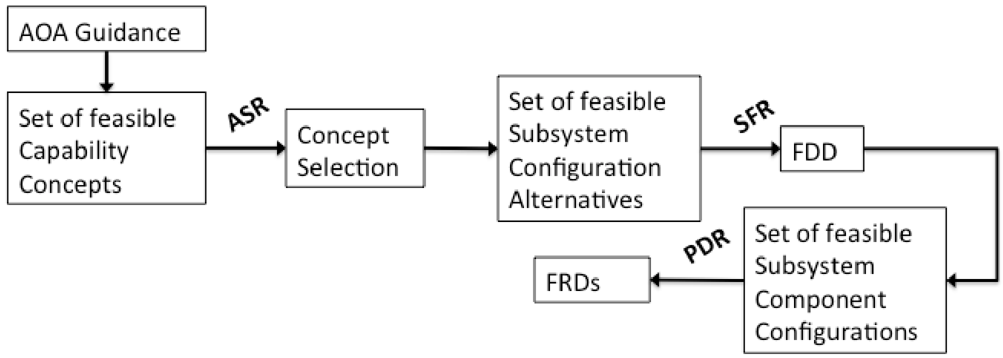

Figure 26. Flow of the Selection of the Subsystem Configuration through PDR.

The completion of SETR-required actions and documentation is required in both PBD and SBD efforts. Therefore, there exist programmatic and logistical items that must be covered as part of the SETR process; examples include revision of the SEP, Software Development Plan, the Program Protection Plan (NAVAIR 2015). These items can require significant effort. Typically, they performed through a combination of program office and either defense industry, Federally Funded Research and Development Center (FFRDC), or government engineering organization activities (DAU 2016). Set Based Design targeted the design of the system itself. Many of these programmatic and logistical items may be DOD, Service, or SYSCOM specific and will be in addition to supporting the SBD execution. One strategy to accomplish tasks outside the SBD activities is through a TD contract, delivery order, or appropriate task order to perform the ancillary SETR activities in parallel to SBD.

The TD contract could be an umbrella effort for which the SBD, programmatic, and logistical items are all elements. In addition to the FRDs developed via the SBD methodology, the TD effort would then complete the other ABL specification documentation not covered by the SDS consisting of the FDD and supporting FRDs. The TD effort would then support all engineering efforts through PDR.

If leadership so decides, the ancillary SETR activities could be accomplished via a discrete effort outside of the SBD effort. If so, care must be taken when constructing Statements of Work (SOWs) to avoid duplication of work. Whether a multiple effort strategy or singular umbrella TD approach is selected, it is important to acknowledge and

plan for these activities that are necessary for a successful PDR that will be outside of the SBD engineering effort.

Upon completion of a positive PDR, the SBD process shifts its focus from ABL development to Product Baseline (PBL) determination. The necessary competitive RFP preparations are completed as normal. The SOW in the RFP will reference the ABL documents resulting from the SBD activities. For the purposes of this scenario study, it is assumed that the SOW requires the use of SBD through the development of the PBL and approval of the PBL at CDR. Once awarded, the EDM contract must be baselined.

Upon completion of the ABL, the design being executed under the EDM contract shifts from finalizing the ABL to the application of SBD principles to potential component configuration solution sets. The design space of potential PBL solutions must be mapped. The feasible region is bounded by the approved ABL. Sets under consideration are the various feasible subsystem component configurations that could be adopted to meet the requirements specified in the ABL. Then the integration by intersection of feasible sets narrows the possible configuration sets (Sobek et al. 1999). These repetitive processes narrow the set of possible component configurations and solutions until the CDR reviews and approves a PBL.

I. ACQUISITION STRATEGY SCENARIO 2

For the second scenario, as described earlier, SBD is performed for a government-led design, i.e., producing a TDP for a vendor to build to print and support Milestone C. The major difference between this scenario and the previous is that government working capital organizations and/or FFRDCs execute the development activities, removing the RFP for system development.

The two scenarios' SBD approaches are identical up through Gate 4. As previously discussed, during Gate 3, the SDS development plan is replaced by the FDD development plan, which includes how the FRDs mature, which in turn carries over to Gate 4. Gate 4 approves the SDS, which for SBD is the collection of the FDD and FRDs as the exit criteria for Gate 4. Sobek and his colleagues' SBD principles (Map the Design Space, Integrate by Intersection, and Establish Feasibility before Commitment), need to

be exercised to pare down the solution set to one baseline system configuration as described in detail in the former scenario. This iteration accompanies the exit criteria of Gate 4 and leads to the PDR, which would best occur prior to Gate 5. As discussed, the customary outcome of PDR is an established ABL placed under configuration control (AcqNotes 2016). Gate 5 is normally the RFP approved for release gate (ASN(RD&A) 2011). With this being a government-led design, a development RFP is not necessary, but that does not mean there is no Gate 5. Instead, Gate 5 aligns with Milestone B to assess the program progress and to approve entry into the EMD phase. Additionally, while the contracting actions may be significantly reduced by not developing an RFP, and all of the associated business clearance to meet government-industry contracting requirements, it should be noted that internal Government Task Orders, Funding Documents, and Statements of Work or Objectives still need to be developed to authorize and fund work to be completed.

As discussed in Scenario 1, Public Law requires ACAT I programs to complete a PDR prior to Milestone B. Other ACATs have the opportunity to hold the PDR before or after this milestone, though the PDR should be held as soon as the design maturity allows. Holding PDR prior to Milestone B should be the goal, regardless of ACAT, to enable better understanding and maturity for the MDA to consider.

FFRDCs and similar government-sponsored research activities perform systems engineering, perform analysis, and often have significant laboratory facilities (Department of Homeland Security 2007). The government (more specifically the Navy) can utilize the existing Naval Research and Development Establishment (NRDE) for the TD phase to prepare for PDR. The NRDE Working Capital Fund model ensures the Warfare Centers remain relevant and responsive to the SYSCOMs and PEOs (U.S. Naval Research Advisory Committee 2010). According to the Federal Acquisition Regulation 6.302-3 paragraph (a)(2)(i), there is no requirement for full-and-open competition when the provision to "establish or maintain an essential engineering, research, or development capability to be provided by an educational or other nonprofit institution or a federally funded research and development center" can be applied (Federal Acquisition Regulation 2016).

This exemption eliminates the need to release an RFP when contracting with organizations such as those, which make up the NRDE. Therefore, leveraging the facilities and workforce within the NRDE to execute the TD phase of the SBD scenario can accelerate the acquisition timeline versus Scenario 1. Since the technical communities of the NRDE are government organizations, intellectual property rights that must be considered when dealing across industry partners is not an issue. This reduces barriers to partnering and sharing of capabilities among organizations in the NRDE. The 14 University Affiliated Research Centers, such as John Hopkins University Applied Physics Laboratory, Pennsylvania State University Applied Research Laboratory, University of Hawaii at Manoa Applied Research Laboratory, and others are another source for technical expertise (AcqNotes 2016). The benefits of a government-led design and the NRDE community, make it an efficient, flexible, and cost-effective network, as these organizations operate at cost, leverage valuable government investments, and are focused on serving the advancement of technology for the betterment of the government and society. This research and development network matures technology and helps determine solutions. Low-fidelity prototyping efforts, utilizing the NRDE in-house capabilities and test facilities to gain knowledge and narrow solution sets, aid in the technology maturation. This enables the design and documentation of the ABL prior to Gate 5.

Gate 5 will enter with the approved ABL and will still align with Milestone B per the traditional SECNAVINST 5000.02E acquisition framework. The effort to resource and complete documentation required to prepare the RFP and select the vendor is immense and time consuming (USD(AT&L) 2015). Therefore, in this scenario, the removal of the RFP allows for the ability to shift some events to the left for earlier execution.

Like Scenario 1, what occurs between Gate 5 and Gate 6 in terms of the SBD application is more trade space exploration and set reduction from PDR to CDR. After the successful completion of PDR, the designers commence detailed design. For example, the NAVAIR SETR process specifies that at PDR, the breadth of design is still being evaluated, validated, and verified, creating an opportunity for continued SBD principles

at a lower level in terms of subsystems and components. The CDR approves the PBL, which "allows the completion of the design to the component level" (NAVAIR 2015, 39). The PBL makes up the specifications needed for inclusion in the build-to-print TDP. At this point, the opportunity for SBD has diminished as the trade space is closed. Once the TDP is developed, the effort moves to preparing for Test Readiness Review, Milestone C, LRIP, and ultimately a full rate production decision.

J. SCENARIO COMPARISON

Each respective scenario covers the spectrum of the most-likely acquisition strategies a program manager may encounter, but is not all-inclusive and every program must tailor these recommendations to meet the needs of the program. The objective was to demonstrate that SBD can be executed effectively whether through one design team or through a vendor handoff. In fact, both scenarios are very similar in expressing how the acquisition strategy is tailorable to incorporate the SBD principles and methodology; both close their respective solution space after the CDR. The major differences, which will be further discussed below, are buried in the process and inherent obstacles of each scenario.

Scenario 1 creates difficulty for the government to manage SBD performance and oversight. It is hard to measure how well SBD performs. It is a methodology that tailors specifically to each program. How the vendor chooses to implement it is their prerogative. A couple key principles of SBD are delaying design decisions and longer periods for stakeholder influence. While the vendor is maturing the design, decisions need close management and documentation in the RFP to ensure the stakeholders are the focal point of the design decisions, not the vendor, driven by profit potential.

For Scenario 2, there is no SBD transition between actors, which allows for a more integrated design development, especially from the ABL to the PBL. The design development is more of a partnership because it is government-to-government. That in nature promotes more stakeholder influence and ownership. There is also the ability to leverage the capabilities amongst the NRDE community, which are diverse, cost effective, and easily accessible.

Table 8 summarizes the comparison between the two scenarios. In this table, key characteristics of program execution demonstrate the amount of influence each scenario has with respect to the characteristic. The government ranks the influence in terms of low, moderate, or high.

Table 8. Scenario Characteristic Comparison Table.

Characteristics	Scenario 1	Scenario 2
Process Flexibility	Moderate	High
Design Control	Moderate	High
Resource Accessibility	High	Moderate
Stakeholder Influence	Moderate	High
Execution Efficiency	Moderate	High
Competition	Moderate	Moderate
Design Risk	Low	High

The first characteristic is Process Flexibility; this refers to the control over the SBD process and its implementation. Scenario 1 is moderate because the government loses control of the SBD execution once the design is turned over to the vendor. However, Scenario 2 the influence is high because the government maintains control of the design, which creates a partnership between the program office and the lead systems integrator.

The second characteristic is Design Control; this references the government's ability to influence the design during synthesis. Again, SBD promotes delaying design decisions until a better understanding of the system emerges, which creates more stakeholder involvement. With Scenario 1, the vendor handoff removes some of that influence, therefore scoring a moderate rating. The vendor in turn would be making some of those critical design decisions in a vacuum to mature the design; this degrades some of the SBD advantage. Scenario 2 scores a high rating because, again, this is government to government, creating an environment of partnering.

The third characteristic is Resource Accessibility; this is the ability to allocate resources to execute the program in an efficient manner. Scenario 1 yields a high rating.

Vendors have the ability to control staffing levels to handle workload changes. Scenario 2 has a moderate rating because staff level management in the government can be difficult. The government does not have the labor flexibility of industry and could have to reach across multiple platforms or organizations to staff projects appropriately.

The forth characteristic is Stakeholder Influence; this is addressed in the second characteristic analysis and is scored similarly between the two cases. The stakeholder influence does decrease with a vendor handoff.

The fifth characteristic is Execution Efficiency; this refers to the program efficiency and ultimately the timeframe associated with delivering the product to the fleet. Assuming all other programmatic factors are equal (i.e., labor, skills, design tools, risks), the opportunity to not have to prepare an RFP and award a contract creates a significant amount of time saving. Therefore, Scenario 1 has a moderate ranking with Scenario 2 receiving a high ranking because of contact award relief.

The sixth characteristic is Competition; this refers to utilizing competition within the program to lower costs and mature technology. Both Scenario 1 and Scenario 2 receive a moderate rating but each promotes competition differently. With Scenario 1, the competition is during the proposal-soliciting phase. Scenario 2 promotes competition by utilizing small contracting vehicles throughout the design cycle to reach industry for more specific purposes. An example of this would be vendors competing for the battery design of an unmanned vehicle.

The final characteristic is Design Risk; this refers to the risk endured by the government with a deficient design. Scenario 1 has a low rating because the vendor assumes the design risk and is under contract to deliver a functioning product. For Scenario 2, since the government executes the design, the government assumes more risk. Deficiencies will require more funding to correct therefore causing a high rating for this particular characteristic.

K. IMPLEMENTATION DIFFERENCES FROM TOYOTA

The SBD Scenarios above provide guidance for implementation of SBD in DOD acquisition. These scenarios aim to meet SBD principles while meeting the intent of the various acquisition policies. However, there are distinct differences between the recommendations and Toyota's original concurrent engineering practices. The most noticeable difference is in the use of prototyping. While both Toyota and DOD focused on multiple prototypes, Toyota "developed prototypes of an extraordinary number of different designs for subsystems" (Sobek et al. 1998, 48) even through the production phase. In the DOD guidance, the team has identified low fidelity prototyping strictly to understand the design space and not look at production benefits. In addition, to maximize the benefit of SBD, the CDR locks down the design. Toyota, on the other hand, utilizes multiple designs even during production.

While the SBD implementations are similar in nature, Toyota's implementation has two distinct benefits. The first is the relationship with its vendors. Toyota is able to take advantage of its relationship with vendors and work with them to expand the design space. The vendors participate in the SBD process and work with Toyota in prototyping. In the DOD guidance, prototyping feeds design requirements for contracting. The winning vendor does not participate in the DOD SBD process but leverages their own SBD approach if required in the contract, in order to reach a converged design. The second benefit is Toyota's ability to continue prototyping beyond the CDR and into production. Toyota is willing to spend more money on the prototyping to find a successful design because they know it will eventually lead to profit via a quicker design to production phase In DOD acquisition, the government cannot afford such lax policies with spending. While SBD has seen some benefit as shown in the case studies, it remains to be seen if the DOD can reap the same benefits as Toyota.

L. TAILORING NAVY ACQUISITION FOR SET BASED DESIGN SUMMARY

This chapter introduced the DOD and Navy acquisition frameworks to detail the administrative structure and tailoring opportunities afforded within the instructions. Defense acquisition directives and instructions, which affect the application of SBD,

were identified. SBD is discussed concerning the core Defense Acquisition Program Models and how hardware intensive systems lend themselves more to the use of SBD as opposed to software intensive systems. The particular tools needed for SBD execution and the programmatic impacts of SBD were discussed, including delaying decisions and ways to communicate effectively in sets. The role of prototyping in SBD and the use of prototyping to gain technical knowledge and narrow the solution space were also examined. Following the discussion, two SBD scenarios were presented and analyzed to demonstrate how tailoring SBD can maximize its benefits. A comparison of the two scenarios follows the analysis to portray the differences of each circumstance.

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V. CONCLUSION

A. SUMMARY

This project examined the potential use of SBD principles and methodologies as a part of Defense Acquisition. Since weapon system acquisition has been plagued by time, funding, and requirement constraints, the benefits of SBD provide motivation for such a study. Further, it sought to provide specific guidance for DOD program managers and systems engineers who may choose to employ SBD. This project answered the following research questions:

1. What is SBD and how can it benefit defense acquisition?

SBD is a system engineering design methodology which is centered around the concept of maintaining an expanded design space to include all design possibilities for as long as practical, while delaying critical design decisions until sufficient information is known to eliminate alternatives that are infeasible (Sobek et al. 1999). The paper examined how, according to Sobek and his coauthors, SBD advocates systematically narrowing the set of possible designs while imposing minimum constraint (1999). Based on the principles set forth in their work, SBD looks for the intersection of the different required system functions among the feasible sets, and eliminates those alternatives outside these overlapping regions (1999). According to Sobek and his cowriters, the principle integrating by intersection contrasts from the PBD methodology, which optimizes functions in a compartmentalized fashion and then attempts to bring the optimized functions together in an integrated solution at the end, resulting in optimized subsystems, but an overall suboptimal system design (1999). By integrating at the intersections (vice optimized silo), a better overall system design can be achieved (1999).

SBD has the potential to benefit defense acquisition programs. However, even though Toyota’s use of SBD proved to be highly successful, employing it as part of government acquisition is a different process. According to the case study of Naval Surface Warfare Center Carderock Division’s three-month design exercise presented by Mackenna and his co-authors, which compared and contrasted the application of PBD

and SBD, SBD is more flexible when faced with requirements changes during design execution (2014). Their results showed how SBD enabled the Carderock SBD team to absorb imposed requirements updates more easily than the PBD team who performed more design rework and assume additional design risk to maintain schedule (2014). A defense acquisition program execution could use SBD to maintain flexibility in the face of externally imposed requirements changes.

Furthermore, through the case study analysis in Chapter III, the following are additional benefits of using. SBD establishes system design feasibility before commitment where design development is not limited to a single solution. Engineers develop parallel system-level designs and delay decisions about system requirements until the understanding of trade-offs is sufficient. The method continually promotes design discovery while allowing flexibility for requirements change. This method defers cost commitment until sufficient design detail permits selection, allowing for a longer period for stakeholder influence and feedback.

2. What factors make a program a good candidate for employing a SBD approach in defense acquisition?

Hardware intensive systems are good candidates for employing SBD. The DODI 5000.02 lists six different acquisition program models, one of which is hardware intensive programs. Hardware intensive systems lead themselves to the development of tradeoff curves and surfaces to allow for easier application of tradeoff analyses among sets of possible solutions, as advocated in SBD. Therefore, hardware intensive programs are good candidates to use SBD.

Programs using SBD should use the correct tools and prototyping. Set Based Design is superior when done with the correct tools, which includes incorporating prototyping into the program baseline. Good candidates for the SBD methodology include those programs that have either access to or the funding available to develop the design analysis tools needed. Programs that seek to utilize SBD should perform sufficient planning and budgeting to employ SBD enabling tools such as FACT, LEAPS, and ASSET early in the design process. In addition, prototyping should be budgeted into the

program prior to establishing the program baseline to support low fidelity prototyping of multiple alternatives to facilitate set reduction.

Set Based Design allows for delaying of system life cycle cost commitment. However, the team predicts that additional costs arise early in the design process to utilize the analysis tools to create low fidelity prototypes to map and narrow the design space. Low fidelity prototyping is a critical enabler for the SBD process pre-Milestone B and will better promote trade-offs and the exploration of the design space. Ensuring sufficient funding is in place at key times in the acquisition process ensures the proper steps to map and reduce design space adequately.

3. What effect does SBD have on overall system costs and risks in support of defense acquisition? Are the potential benefits worth it?

Set Based Design focuses on delaying cost commitments until there is sufficient knowledge to make proper decisions while mapping and narrowing the design space. When delaying cost commitments, management and team members have a longer duration of influence, which reduces risks to the program (Singer et al. 2009). Feedback flows into the system design, as more information about design requirements become apparent and better understood. SBD requires increased funding earlier in the program to map properly the design space versus the alternative PBD methodology. Higher upfront costs, in order to utilize tools and create multiple low fidelity prototypes to achieve a more global solution, are worth it, as the outcome is closer to meeting user requirements when delivered to the fleet, resulting in lower overall cost and risk. In theory and in practice in the commercial world, SBD is a better alternative for both cost and risk. Unfortunately, there is very little literature available on implementation of SBD in DOD acquisition. It remains unknown if SBD can bring the same benefits to defense system acquisitions as it has to industry.

4. What instructions and processes would have to be tailored or revised to facilitate PORs to use SBD in their development activities?

The incorporation of SBD within acquisition programs will likely require tailoring of existing DOD processes. However, SBD can be accommodated within the existing

instructions without revision. DODI 5000.02 reiterates the authorization for MDAs to tailor programs to meet the DODD 5000.01 primary objective (USD(AT&L) 2015). Tailoring of processes, reviews, or procedures to incorporate and take advantage of SBD design processes is available to the MDA as they see appropriate (USD(AT&L) 2015). SECNAVINST 5000.2E describes an overview of the Navy's acquisition management process including the 2-Pass/6-Gate DON Requirements and Acquisition Governance Process (2011). The application of this process will need to be tailored to best incorporate SBD into the development Navy systems. The two scenarios provided in Chapter IV show examples of tailoring the 2-Pass/6-Gate process to employ better SBD within the Navy's acquisition process.

B. REVIEW OF TAILORED SET BASED DESIGN SCENARIOS

Using lessons learned from the SBD DOD case studies, attributes and commonalities were examined to form guidelines for SBD implementation within the SECNAVINST 5000.2E 2-Pass/6-Gate process. Two different acquisition strategy scenarios were analyzed, one utilizing an RFP to award the design to a vendor, while the other being a government led design effort. Each scenario should implement the SBD methodology in a comparable manner with the tailoring of the gate entrance and exit criteria to promote SBD characteristics. The SBD process can be partitioned into two major phases. The pre-Milestone A phase consists of mapping and defining the requirements space. The post-Milestone A phase consists of mapping and defining the material space and narrowing the solution sets to the best-valued design. The CDR, or product baseline, is the most appropriate place to determine the design space. At this point in the acquisition process, continuing to make design changes (leaving trade space open), may be costly and inefficient. The differences of each SBD scenario emerge when comparing programmatic characteristics such as process flexibility, design control, resource accessibility, stakeholder influence, execution efficiency, competition, and design risk within the bounds of each acquisition strategy. While utilizing SBD, it is best executed within the government led design team construct. There are also notable differences with how industry, such as Toyota, leverages SBD versus the government's

ability to execute the methodology. These constraints are inherent of the nature of DOD acquisition and Toyota's profit driven business model.

C. FURTHER RESEARCH AREAS

A detailed analysis of applicable SBD processes for potential SBD programs or platforms would be useful. Further research should look into the development of targeted acquisition strategies for possible programs, followed by the examination of specific SETR checklists. Growing and maturing MBSE tools to perform SBD analyses and eliminate alternatives is another area that would advance SBD in the world of systems engineering. This would enable more fidelity in the specific deliverables applicable to SBD. Developing SBD guidelines for more program acquisition models such as the accelerated and incrementally deployed models would help future program managers. Additionally, further education and training of the government workforce to employ existing tools is needed; in parallel, standardization of SBD tools and mechanisms used ought to be investigated.

D. CONCLUSION

This paper provides the guidelines and assumptions for how to apply the SBD methodology within the constructs of the DOD acquisition framework. Resources, risks, and programmatic factors are evaluated against the PBD methodology. These recommendations are just the first steps for the long-term successful use of SBD within the DOD. The initial foundation for applying SBD to DOD acquisition has been built with a clear understanding of how to execute its core principles and leverage its key characteristics while abiding by the acquisition instructions. The recommendations provided in this paper attempt to break the ground of incorporating the SBD methodology within the DOD, a mammoth endeavor.

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